

ABSTRACT

(Bell & Howell)

Testing Forestry Best Management Practices for Protecting Water Quality in Honduras

by

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This study tested the effectiveness of Forestry Best Management Practices (BMPs) during two consecutive years (1999 to 2000) to reduce erosion and sedimentation rates in the pine forests of Honduras. Soil losses were measured from logged pine forest areas and from forest roads. The Universal Soil Loss Equation (USLE) and the WEPP Model (Water Erosion Prediction Project) were also compared with actual erosion to determine their accuracy. Results showed that BMPs such as cable logging, animal logging, slash treatment, water bars, road surface treatments, and revegetation of cut and fill slopes of roads are highly effective in reducing from 50% to 90% of erosion rate, while the tested erosion models resulted very inaccurate.

CHAPTER 1

INTRODUCTION

Background of the problem

In Honduras, two major river systems drain the central highlands to both the Caribbean Sea (eight river basins) and the Pacific Ocean (two river basins) (Gutierrez 1992; Laboranti 1982). The average precipitation rate is 2,000 mm per year and this rainfall produces significant runoff from watersheds (Hargreaves 1992). Since Honduras is a narrow strip of land, rivers run from the continental divide (2,000 meters above sea level) to the lowlands in the Pacific and Caribbean coasts in very short distances. As a result, rivers are typically steep, enclosed in v-shaped valleys, and exhibit dendritic drainage patterns (Hirt et al. 1989). The country has no wide, deep navigable rivers. An impermeable, semi-compacted soil layer underlies a thin soil surface which increases the risk of flash floods during the rainy season (Hargreaves 1992). This results in low ground water storage capacity with streams returning to base flow almost immediately after rainfall events (Hargreaves 1992). Due to this effect, water is not available throughout the year for most parts of the country.

Forests in Honduras are being depleted at an accelerated rate (Government of Honduras 1991). The deforestation rate is currently 80,000 hectares per year (Rivera et al. 1998), which is one of the highest deforestation rates in the hemisphere (Stonich 1983). Inadequate forest planning and management have resulted in significant impact to the water resources of Honduras (Campanella 1982). Water quality degradation from non-point

sources related to timber harvest is a serious problem in Honduras (Campanella 1982; OEA-UNAH 1992). Current forest management activities have resulted in declining soil productivity and water quality in forested watersheds. Timber harvest and road-building operations have produced large quantities of sediment (OEA-UNAH 1992) resulting in the sedimentation of reservoirs, and the deterioration of water quality (Chavez 1992; ENEE-CIDA 1995; Gollin 1994; Campanella 1982; COHDEFOR 1996). As a result, only 30% of the water in Honduras reaches the water quality standards established by the Pan-American Health Organization (OEA-UNAH 1992; Honduras 1991).

Almost 85% of the Honduran water supply for domestic use depends on surface water (Government of Honduras 1991). Surface water contamination has reached critical levels in both rural and urban areas (Leonard 1987). Some rivers, like the Choluteca River, have water quality that is significantly lower than the standards established by the American Health Association and the US Environmental Protection Agency (OEA-UNAH 1992).

Since Honduras is located in the tropical zone, physical characteristics of the country accelerate erosion processes. Rainfall generally exceeds evapotranspiration during three or four months in an average year. In the eastern portions of Honduras rainfall can exceed evapotranspiration for seven months. Greater than half of Honduras might experience 300 mm of rain in 24 hours (Hargreaves 1992). Soils are formed from metamorphic, volcanic, and sedimentary parent materials. As a result, eight of the ten world soil orders exist in Honduras. These soils are classified with a high to very high erosion risk. In addition, the terrain in Honduras is characteristically steep with 75% of the territory having slopes greater

than 30% (Government of Honduras 1991). Most soils are underlain by slowly permeable material so that deep percolation of water is limited (Hargreaves 1992).

These three factors, high runoff, erodible soils, and steep terrain combine to produce high erosion and consequently, high sedimentation rates. For instance, the Jicatuyo River in the northern part of the country has a sedimentation rate of 215.3 m³/ha/year, which is relatively high compared to temperate environments (Laboranti 1992). High erosion rates become problematic when compounded by forest management practices that are not appropriate or well designed. Forestry practices intended to protect water quality have been ineffective in Honduras (Laboranti, 1992). In addition, improper watershed management has led to flooding and water contamination (Campanella 1982).

The development of a set of forestry Best Management Practices (BMPs) to protect water quality was initiated by COHDEFOR in 1994. A set of forestry BMPs was completed in 1998 (Rivera and Kershner 1998) and operational testing lasted from 1998 to 2001. During this period of time, we tested the practicality and efficiency of these forestry BMPs .

Purpose and Project Goals

Best Management Practices (BMPs) are a set of measures designed to minimize the amount of pollutants sediment produced during logging and road building operations and other land management activities (Harper 1979). These practices have been used effectively in the United States, but have never been designed for or tested in tropical or temperate forests of Central America.

The purpose of the proposed research is to determine the effectiveness of forestry BMPs in protecting water quality during timber sale operations in Honduras. We tested the efficiency of these practices in retaining and reducing the amount of sediment entering water bodies, and determined the adequacy of the proposed BMPs.

The goal for this project was to test the effectiveness of selected forestry Best Management Practices in controlling non-point sources of sediment during logging and road building operations.

The specific objectives were to:

1. Determine and compare soil loss from treated sites (BMPs implemented) and untreated sites (traditional harvest methods) during forest harvest.
2. Determine and compare soil loss from treated (BMPs implemented) and untreated sites (traditional road construction practices) during forest road construction.
3. Test the precision and accuracy of the USLE and WEPP models in predicting the erosion rate for the forest conditions in Honduras.
4. Determine and compare soil losses from each BMP by conducting experiments using a rainfall simulator.
5. Refine and redesign BMPs using the results of this study and suggest alternate BMPs based on our experiences.

Study Area Description

Honduras is located in the center of the Central American isthmus, between 13° and 16° latitude North and 83° and 89.5° longitude West (Figure 1-1). It has an area of 112,088

square kilometers (Leonard 1987). It is a rich country in terms of natural resources and has the highest percentage of forest lands among the other Central American nations (Humphrey 1997; Campanella 1982; COHDEFOR 1996). Approximately 50% of the country is still covered by undisturbed forests (Richards 1996; Rivera et al. 1998) which include humid tropical forests, arid or deciduous tropical forests, cloud forests, mangrove wetlands, and pine forests (Humphrey 1997; Rivera et al. 1998). Tropical forests are typically associated with coastal mountains receiving high amounts of precipitation while pine forests are located in the headwaters of rivers in the mountains of central Honduras.

Under natural conditions, the potential for rainfall erosivity is very high in Honduras (Mikhailova et al. 1997; Salas 1987). Erodible soils, steep terrain, and high runoff combine to produce high erosion and subsequently, high sedimentation rates. Soils are formed from metamorphic, volcanic, and sedimentary parent materials and have a high to very high erosion risk (Simmons and Castellanos 1969). These soil formations are associated with steep terrain and 75% of the forest lands have slopes greater than 30% (Simmons and Castellanos 1969). Estimates of erosion based on the USLE in the mountainous lands of Honduras ranged from 0 to 60 kg/ha/yr soil loss (Zavgorodnaya de Costales 1990). Actual erosion rates in pine forests of Honduras have been measured at approximately 40 kg/ha/yr (Hudson et al. 1983).

This study was conducted in the pine forests of the National School of Forest Sciences (ESNACIFOR) (Figure 1-1), located 3.5 km to the southwest of the town of Siguatepeque, Honduras. The study area is located within the El Cajon watershed which

provides the nation's largest reservoir and is the source for 70 percent of the country's hydropower (Gollins 1994). The area is mountainous with elevations ranging from 540 to 2,500 m above sea level. Most of the forest is located on slopes greater than 40%. The soils are well-drained Lithosols of the series Cocona with a sandy loam texture and a pH ranging from 5.0 to 6.0 (Simmons and Castellanos 1969).

Literature Review

Non-point source pollution from forest harvest activities may alter forest productivity, cause deterioration of drinking water, and affect aquatic life (US EPA-US Forest Service 1980). Pollutants from silvicultural activities include sediment, pesticides, petrochemicals, and wood waste (US Forest Service 1983; Bailey and Waddell 1979). Of these pollutants, fine sediment production has the most significant impact to water quality (US EPA-US Forest Service 1980; Ashcroft and Brown 1995). Fine sediments that enter streams may lead to decreased dissolved oxygen, increase turbidity, and elevate nutrient levels that might affect the photosynthetic production in streams (Lynch et al. 1985; Brooks et al. 1991) and lakes (Logan 1993).

The majority of sediment production from forest harvest practices comes from timber harvesting and roads. The construction of forest access roads alone is responsible for more than 90% of sediment produced during logging operations (Brooks et al. 1991; Sidle 1980; FAO 1989; Megahan 1980; Keller 1997). The most common features in logging and road construction activities and the approximate amount of sediment produced during these activities are shown in Table 1-1.

Best Management Practices (BMPs) are techniques developed to prevent and reduce water pollution from non-point sources by controlling specific critical areas and practices that produce sediments (US Forest Service 1983).

The term non-point source pollution refers to pollution that cannot be attributed to a specific point and is usually associated with land use activities such as crop cultivation, urban development, mining, grazing, logging, and road construction (Brooks et al. 1991; US Forest Service 1983). By contrast, point-source pollution refers to a specific point of contamination such as a pipe, ditch or channel discharging contaminated substances into a water body (Loehr 1978). The BMP concept has been used since 1949, but it did not attain legal standing until 1975 as a part of Section 208 of the 1972 Clean Water Act (Ice et al. 1997). Since then, the Environmental Protection Agency (EPA) has developed regulations to guide states in implementing these practices (MacDonnald et al. 1991). By 1982, most states had developed some type of silvicultural BMPs to reduce and prevent non-point source pollution (Ice et al. 1997).

BMPs are developed by the management agency in charge of a designated area or activity and must be reviewed and approved by the state agency responsible for water quality protection (Harper 1979). BMPs must be effective, practical, economically and technically feasible, and compatible with current environmental laws and institutional regulations (US Forest Service 1983, 1993; US EPA-US Forest Service 1980). Some BMPs consist of administrative and legal procedures while others are a set of technical procedures. In

essence, BMPs focus on reducing non-point source pollution by mediating the relationship between human land use and natural processes (Harper 1979).

The most common silvicultural BMPs designed to reduce the actual input of sediments into streams include buffer strips along stream channels, proper skidding of logs, installation of water bars on skid trails, revegetation of disturbed areas (fills and cuts), filter windrows on fill slopes, adequate surface and subsurface drainage structures, proper logging systems, management of harvesting residues, and proper location and design of all haul roads, landings, and skid trails, etc. (Lynch et al. 1985; Logan 1993; US Forest Service 1983). A number of studies have shown that BMPs have been highly effective in controlling non-point source pollution and reducing actual pollutant output (Clausen and Meals 1989; Moore et al. 1992; Lynch et al. 1985; Ketcheson and Megahan 1996; US Forest Service 1997[b]). The most common silvicultural BMPs and their efficiency in controlling sediments entering streams are shown in Table 1-2.

Most tests of BMPs have been conducted in agricultural (Moore et al. 1992; Lynch et al. 1985) and urban (Dennison 1996; US EPA 1993) lands. A seven-year study in a Vermont agricultural watershed showed that BMPs were highly effective in reducing pollutant concentrations and loads (Clausen and Meals 1989). In Tennessee, researchers found a 50% reduction in watershed erosion and stream sediment loads when a set of BMPs were applied to an agricultural watershed (Moore et al. 1992).

There are few tests of BMPs in forest lands and these have produced ambiguous results. For example, tests conducted on sixteen national forests in California showed that

water quality was significantly better in places where BMPs were implemented (US Forest Service 1993). In contrast, a watershed study in Tennessee found no apparent changes in water quality when state BMPs were implemented in harvest operations (Moore et al. 1992). Similarly, a qualitative assessment of water quality in South Carolina streams found no differences in water quality between timber harvest areas treated with BMPs and those having no BMPs (Ice et al. 1997).

Typically, the effectiveness of BMPs is determined either by direct measures of water quality such as suspended sediments and bedload in stream channels (in-stream or in-channel evaluation) (Kunkle and Thames 1976) or by evaluating sediment yield from plots adjacent to the treatment (Foster and Lane 1981). Instream assessment of BMPs may be confounded due to the cumulative impact of various sources of pollutants within the watershed (MacDonald et al. 1991; McClurkin et al. 1987; Asselman 1999) and the great natural buffering capacity of watersheds to absorb the adverse effects (Brooks et al. 1991). On-site measures are sometimes preferred to evaluate BMPs, since the impacts to water quality measures (in-stream measures) are more difficult to control. On-site measures are usually capable to assess whether the proposed practice has the desired effect (MacDonald et al. 1991). These methods minimize the variation in sediment production measured at large scales.

Monitoring surface erosion at the site provides information on whether the BMPs offer adequate water quality protection. Surface erosion can be measured by several field methods. The most common methods include the use of runoff plots and erosion stakes

(Brakensiek et al., 1979; Brook et al. 1991; Lal et al. 1997). The runoff plots are designed to measure the amount of soil that washes from the plot (Figueroa et al. 1983). Sizes can vary, but the standard size is 2 x 22 m (0.004 ha). Collecting tanks are buried along the bottom of the plot and instruments record flow rate and total volume of water and sediments that are produced from each storm. Erosion stakes also are used to measure soil losses and sediment deposition (Blaney and Warrington 1983). Stakes are arranged in a grid pattern along hillslope profiles and repeated measurement of the stake elevation provides an estimate of soil lost and deposited during each storm. These have been the basic methods of measuring water erosion for many years. Recently, new methods are being developed which include the use of GPS techniques and geographic information systems to detect the movements of soil particles due to natural and man-made processes (Zhang et al. 1996; Chaves and Nearing 1996).

Rainfall simulators are becoming more frequently used to determine hydrologic characteristics of specific areas managed under various scenarios (Meyer and Harmon 1977, 1979; Mutchler and Hermsmeier 1965). Data can be obtained more rapidly, thus saving time and money and improving the quality of the data through simulated rainfall (Wallin and Harden 1996). In experiments with artificial rainfall, arrangements can be made at the research plot depending upon the conditions being evaluated. In fact, this is the main importance of using a rainfall simulator (Meyer and Harmon 1979; Dobrowolski, 1998; Alcala et al. 1998). Rainfall simulators can be used to determine the individual effect of each specific BMP and isolate the confounding effect of other practices (Hall 1970).

Erosion simulation models can also be used to evaluate the performance of BMPs (Foster and Lane 1981; Laflen et al. 1991; Elliot et al. 1995[a][b]). A wide variety of simulation models designed to predict erosion have been used since the creation of the Universal Soil Loss Equation (USLE) and its other versions, Modified Universal Soil Loss Equation (MUSLE) and Revised Universal Soil Loss Equation (RUSLE) (Brooks et al. 1991). These computer models are based on the principles of the USLE (soil erodibility, rainfall erosivity, topography and management), but the calculations of some empirical parameters has been changed to represent more process-based relationships (Laflen et al. 1991). Some applications of USLE have been implemented on forest settings (Dissmeyer and Foster 1980) and tropical conditions (Viana 1990; Silva 1997). Computer simulation models include Chemical, Runoff, and Erosion from Agricultural Management Systems (CREAMS), Erosion/Productivity Impact Calculator (EPIC), Simulator for Water Resources in Rural Basins (SWRRB), Simulation of Production and Utilization of Rangelands (SPUR), Areal Non-point Source Watershed Environment Response Simulation (ANSWER), Agricultural Non-point Source Pollution (AGNPS), and the Water Erosion Prediction Project (WEPP) model (Purdue University 1998; Elliot et al. 1993).

The WEPP model is currently believed to be the best erosion prediction model for forested landscapes (Elliot et al. 1993; Laflen et al. 1991). This model is a continuous simulation program designed to predict soil loss and sediment production and deposition from overland flow on hillslopes (Nearing et al. 1990). The WEPP model estimates spatial

and temporal distributions of soil loss and deposit and also provides an assessment of when and where erosion-deposition is occurring along the hillslope profile (Laflen et al. 1991).

Initially, the WEPP model was developed for agricultural and rangeland conditions (Chaves and Nearing 1996). Research is currently in progress to evaluate the application of WEPP to forest conditions, including harvested areas and forest roads (Elliot et al. 1995[a][b]). At present, input files have been developed to model road surface, timber harvested areas, forest fires, and forest cut slopes (Elliot 1996; Elliot and Hall 1997). Results have shown that the WEPP model is well suited to predicting erosion in a variety of forest conditions (Morfin et al. 1996; Foltz and Elliot 1996; Foltz 1996) and is useful in assisting managers in the design of water bar spacing and buffer zone widths adjacent to streams. The model has been used to predict the optimal cross drain spacing necessary to reduce stream sediment delivery and the USFS is currently using the model to design new guidelines for road cross-drains (Morfin et al. 1996; US Forest Service 1997[b]). Other studies have shown that runoff values predicted by the WEPP model were very close to the observed values on forest roads (Elliot et al. 1995[a][b]). Previous evaluations of the WEPP model indicate that the coefficient of determination (r^2) between observed and predicted erosion was 0.77 for single storm events, 0.76 for annual values and 0.87 for average annual values (Zhang et al. 1996).

The WEPP model may also be useful for testing the efficiency of BMPs (Elliot et al. 1993). WEPP can be used to predict the location of soil detachment and deposition on a hillslope. The model is composed of four input files: slope, soil, climate, and

management (USDA-WEPP 1995). BMPs modify all of these files except the climate file. The BMPs reduce slope length along the hillslope profile, reduce soil bulk density, and increase infiltration by leaving buffer strips, revegetating disturbed features, and leaving harvest residues on the forest floor in the model. In essence, the BMPs change the surface roughness and flow path direction in the model thus reducing surface runoff volume by increasing infiltration. Once the WEPP model is calibrated for the study conditions, it can model the erosion process and provide an accurate output of sediment leaving the hillslope profile. This output can allow for the modification of the original BMP design. The WEPP model output, especially the sediment leaving the slope, could suggest a larger or smaller spacing for water bars, rolling dips, open culverts, and other drainage control structures, depending upon whether the sediment is retained or released. Additionally, this model might be used to predict erosion more accurately and could be useful for designing an erosion hazard system and mitigation measures (Foster and Lane 1981). Instead of measuring actual erosion, which is costly and time consuming, the model might provide a prediction of the efficiency of the management techniques being used. The testing, modification and improving of BMPs could then be made more rapidly and more efficiently.

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Table 1-1. Summary of sediment production according to different silvicultural activities

Disturbance Feature	Sediment Production	Source(s)
Clearing of vegetation, forest fires	*887 kg/ha/yr	*Hudson et al. 1983
Skid trail	*3 cm/yr soil loss *reduces soil hydraulic conductivity by 100%	*Seyedbagheri 1996
Pioneer road	*0.5 ton/km (in first week)	*Gray and Sotir 1996
Cut slope	*40.4 ton/ha/year *2.5 cm/year	*Burroughs and King 1989 *Seyedbagheri 1996
Fill slope	*1.27 cm/year	*Seyedbagheri 1996 after Jensen and Finn 1966
Inappropriate culvert size on first and second order streams	*9% of gully erosion	*US Forest Service 1997[a]
Unsealed road surface	*14-26 ton/km/year	*Gray and Sotir 1996
Road cut slope	*intercepts 35% of total subsurface flow	*Megahan 1977
Road tread (graded surface)	Grade Sediment yield *6% grade = 21 ton/ha/yr *9% grade = 37 ton/ha/yr *13% grade = 71 ton/ha/yr	*Vincent 1985
Road construction	*Represents 90% of sediment in logging *125-225 ton/km/year *up to 500 ton/km/year *exceeds 95 ton/ha/year *2.2 landslides/km, average volume = 460 m ³ /slide, 19% delivered to streams *0.02 ton/ha/day; 770 times over natural rate	*Megahan 1977; 1980 *Clayton 1980 *Seyedbagheri 1996 *FAO 1989 *Megahan et al. 1979 *Megahan and Kidd 1972

Table 1-2. Most common silvicultural BMPs and their efficiency in retaining sediments.

BMPs	Efficiency	Source
Use of cable logging (skyline) over tractor logging	*Produces 6 times less erosion *10% of disturbed area *50% less erosion	*Megahan 1980 *Seyedbagheri 1996 *Cromack et al. 1979
Tractor vs skidder logging	*6.5% vs 3.5% soil removal	*Clayton 1980
Choosing skid trail system that most fits terrain	*50% reduction of erosion	* Studier et al. 1984; Oregon State University 1983
Revegetation of disturbed features	*Reduces landslide to less than 80% *Reduces erosion 5 times	*Megahan et al. 1979 *Gray and Sotir 1996
Installation of water bars + scattered slash + rocks	*Reduce erosion (erosion rate not documented)	*Turton et al. 1992
Wetland Management Zone, 10-60m	*Reduce damages to WMZ=s (erosion rate not documented)	*Washington State Board 1992
Slash scattering to a depth <30 cm	*Reduced erosion (erosion rate not documented)	*Dubleby and Russell 1942
Slash lopping and scattering + mini check dams	*Reduced erosion (erosion rate not documented)	*New Mexico State Forestry 1990
Installation of dips, water bars, and cross drains	*Reduced erosion (erosion rate not documented)	*FAO 1989; Megahan 1984
Fill slope angle < 36E, 67% or 1.5:1	*Reduced erosion, increase stability	*Seyedbagheri 1996; FAO 1989
Road windrows	*Reduced sediment travel distance by 95%	*Seyedbagheri 1996; FAO 1989
Seeded cut slopes	*Reduced erosion by 36%, first year	*Burroughs and King 1989
Angle of repose for sidecasting material < 60-	*Reduced erosion (erosion rate not documented)	*FAO 1989

70%		
Adequate road maintenance	*Reduced erosion by about 40%	*Seyedbagheri 1996 after Grayson et al. 1993
Road surface treatment	*Reduced erosion by 21.5 times	*Seyedbagheri 1996 after Rice and Lewis 1990
Riprapping, energy dissipaters	*Reduced erosion by protecting the outlet of drainage structures	*Haupt, Richard et al. and Finn 1963; Montana Division of Forestry 1994
Road ditches 2-8% slope	*Reduced erosion, aggradation-deposition	*Megahan 1977; Montana Division of Forestry 1994
Installation of culverts	*Reduced erosion in roads by 20%, reduced sediment delivered to stream by 35% mass wasting	*Megahan 1977; Montana Division of Forestry 1994
Insloping, Outsloping and Crowning	*Reduced water ponding on road surface	*Megahan 1977; FAO 1989; Connecticut Forestry Committee 1990
Tree planting (reforestation) Revegetation	*Reduced erosion 63% *Reduced erosion 43%	*Megahan 1978 *Helvey and Fowler 1979

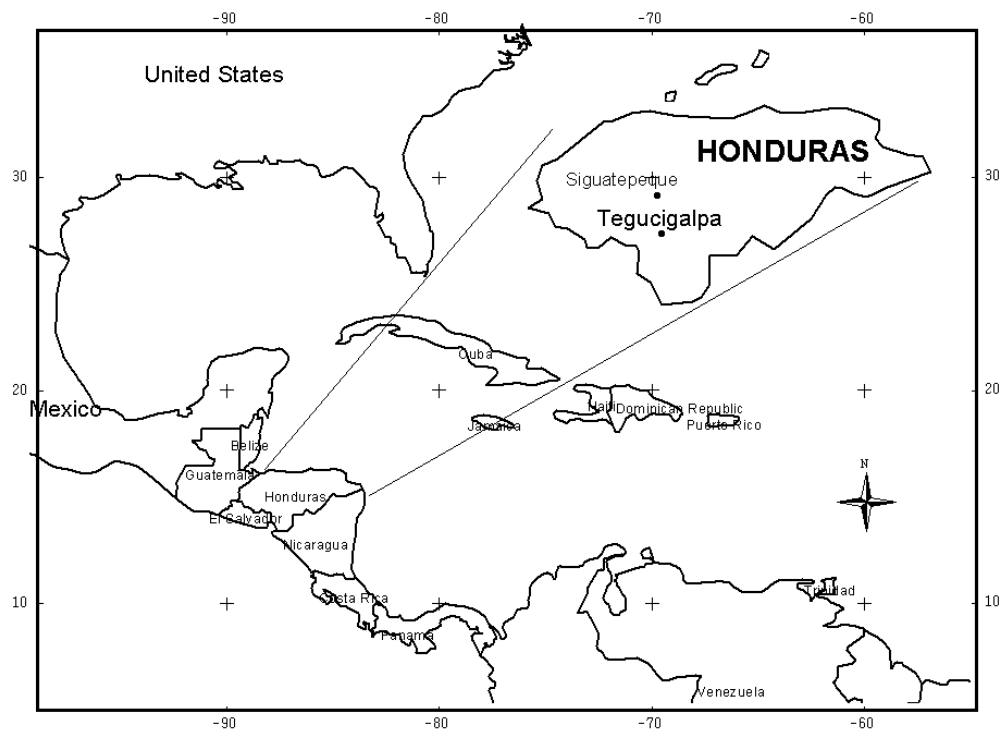


Fig. 1-1. Location of study site in Siguatepeque, Honduras, Central America.

CHAPTER 2

TESTING BEST MANAGEMENT PRACTICES (BMPs) IN FOREST HARVESTING
ACTIVITIES IN HONDURAS¹**Abstract**

Timber harvesting Best Management Practices (BMPs) were evaluated for two consecutive years through field experiments in the pine forest headwaters of central Honduras. Different timber harvesting systems were applied in two watersheds during the rainy seasons of 1999 and 2000. In the first watershed (1999), the applied treatments were tractor logging and skyline cable (BMP), while in the second watershed (2000) four treatments were used: tractor skidding, skyline cable (BMP), animal skidding (BMP), and undisturbed forest (control). During the rainy seasons of these two years, runoff volume and runoff sediment yield were measured at erosion plots of each treated area. A rainfall simulator was used to extend the sampling period beyond what natural rain would provide and to isolate the individual effect of each BMP. The results showed significant differences between the use of BMPs and traditional logging methods. Tractor logging produced from six to ten times more erosion than cable and animal logging. Cable logging, animal logging, and slash treatment were highly effective, reducing by up to 90% of the soil being eroded from the harvested areas, especially during September when the highest rainfall occurs

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Introduction

Stream sedimentation from forest practices is a serious problem worldwide and can result in declining soil productivity and water quality (Walling 1994). Improper timber harvest practices can result in blocked streams, degraded water quality, destroyed bridges and road right-of-ways, ruined fish spawning sites, lowered soil productivity, and property damage (FAO 1989; Megahan 1980; Sidle 1980; US Forest Service 1983; Cromack et al. 1978). In the United States, the Clean Water Act (1972), specifically Section 208, addresses the control of non-point source pollution and gives each state the authority to regulate the control of non-point source pollution. Various federal and state agencies have developed practices to control non-point source pollution from forestry operations and by 1982 most states had implemented practices to control non-point source pollution from forestry practices (Ice et al. 1997).

Best Management Practices (BMPs) are techniques developed to prevent or reduce water pollution from non-point sources by protecting specific critical areas and controlling practices that produce sediments (US Forest Service 1983). BMPs are to be determined by the management agency in charge of a designated area or activity and must be reviewed and approved by the state agency responsible for water quality protection (Harper 1979). BMPs should be effective, practical, economically and technically feasible, and compatible with current environmental laws and institutional regulations (US Forest Service 1983, 1993; US EPA-US Forest Service 1980). Some BMPs consist of administrative and legal procedures while others are a set of technical procedures. BMPs are designed to reduce non-point source pollution by mediating the relationship between human land use and natural processes (Harper 1979).

The US Forest Service has developed a number of Best Management Practices that are implemented during forest operations and are designed to control pollution-causing activities from forest operations (US Forest Service 1983). Common forestry BMPs include: no harvest zones adjacent to streams and lakes, water diversion structures on roads and trails, revegetation of disturbed areas, and the use of logging systems that minimize ground disturbance on steep slopes with highly erodible soils (US Forest Service 1983; Lynch et al. 1985; Logan 1993).

The most common forestry BMPs used to reduce the actual input of sediments into streams include: buffer strips along stream channels, installation of water bars on skid trails, revegetation of disturbed areas (fills and cuts), filter windrows on fill slopes, adequate surface and subsurface drainage structures, proper logging systems, management of harvesting residues, and proper location and design of all haul roads, landings, and skid trails, etc. (Lynch et al. 1985; Logan 1993; US Forest Service 1983). A number of studies have shown that BMPs have been highly effective in controlling non-point source pollution and reducing pollutant output at the watershed scale (Clausen and Meals 1989; Logan 1993; Moore et al. 1992; Lynch et al. 1985; Ketcheson and Megahan 1996; US Forest Service 1997).

The purpose of this study was to compare soil losses from treated and untreated sites during forest harvest. The treatments included timber harvesting using skyline cable (BMPs), tractors (traditional harvesting), animal logging (oxen, BMPs), and undisturbed forest (control, no-harvesting). Runoff volume, infiltration rate, and runoff sediment content were also evaluated at each erosion plot. The hypothesis tested in these

experiments was: sediment yield and runoff volume from the treated (BMP logging methods) plots are equal to the non-treated plots (traditional logging methods).

Study Area

Honduras is located in the center of the Central American isthmus, between 13° and 16° latitude North and 83° and 89.5° longitude West (Figure 1-1). It has an area of 112,088 square kilometers (Humphrey 1997). It is a rich country in terms of natural resources and has the highest percentage of forest lands among the other Central American nations (Campanella 1982; COHDEFOR 1996). Honduras has two types of forest; pine forest located in the central, southern and western parts of the country, and tropical (broadleaf) forest located mainly in the northern and eastern part of the country. Forests cover about 50% of the country's territory and are divided into broadleaf forests occupying 27,458 square kilometers, and pine forest occupying 27,477 square kilometers. Roughly 57,000 square kilometers are covered by other land uses including: agriculture, grasslands, etc. (Rivera et al. 1998).

This study was conducted in the experimental pine forests of the National School of Forest Sciences (ESNACIFOR) (Figure 1-1), located 3.5 km to the southwest of the town of Siguatepeque, Honduras. The area is mountainous with elevations ranging from 800 to 1,500 m above sea level. The forest is predominately *Pinus oocarpa*, with understory of several forbs and grasses. Currently, a Forest Management plan approved by the forestry government agency indicates that these pine areas can reach densities up to 400 mature trees/hectare in a rotation period of 35 years (COHDEFOR 1996).

Typically, due to the high photosynthetic activity, a pine tree can reach from 30 to 40 cm diameter and 20-m height in a period of 20 years.

The study area has a tropical climate with an annual mean temperature ranging from 17° to 28° C (Hargreaves 1992). Annual precipitation is around 1,200 mm and the climate consists of a dry season (from November to May) and a rainy season (June to November) (Hirt et al. 1989). Because most soils are underlain by relatively impermeable material, deep percolation of water is limited, especially in the upland areas. Precipitation surplus has been demonstrated to be the major contributor of surface runoff from watersheds (Hargreaves 1992).

Methods

Natural rainfall experiments

Both control and timber harvest treatments were located in each two first-order watersheds of the ESNACIFOR's school forest (Figure 2-1). The first watershed was harvested during January of 1999 and the other in January of 2000 year. The harvesting method used was the seed tree harvest, which is also a regeneration method, in which mature trees are extracted and middle-aged trees are left standing to provide seed for a new tree generation. After harvesting, the runoff plots were set up and erosion measurements commenced during the following two rainy seasons (June through September/1999 and August through October/2000, respectively). The treatments for the first watershed in 1999 were: cable logging, and tractor logging (Figure 2-1). Treatments for the second watershed were: cable logging, tractor logging, animal logging (oxen), and

undisturbed forest (control). In both watersheds, five runoff plots were located within each treatment area. Harvesting was conducted during the dry season on both areas and equipment operators were not told about the experiments.

The runoff plots (replicates) were established randomly at the approximate center of each treatment or harvest unit. These 10 m x 1.5 m-runoff plots were aligned with the slope of the unit (Figure 2-1). Plots were delineated by driving strips of thin-gauge sheet metal (25 cm width) into the ground (7 cm) and a metal collector was dug into the lower end (McClurkin et al. 1987; Figueroa et al. 1983; Wischmeier and Smith, 1978).

Dimensions of the metal collector were determined by calculating the maximum runoff volume for a storm recurrence interval of 5 years.

All treated areas were harvested and all runoff plots were set up in a range of 30 to 45% slope. The experimental treatments included:

Tractor logging - at the felling site, manually felled trees were dragged using the crawled tractor winch through a skid trail (log full length was dragged over the terrain) and transported to a log landing where logs were loaded into a truck bed.

Cable logging - once the trees were felled manually, logs were fully suspended as they were transported uphill by a cable system that operated with a regular winch. No skid trails were constructed in this operation.

Animal logging (Oxen) - at the felling sites, logs were cut in smaller lengths, loaded by hand in a small cart pulled by oxen, and transported down the hill to a log landing.

Control (undisturbed forest) - the second year, runoff plots were installed in an undisturbed forest, with *Pinus oocarpa*. The understory had different grasses, dominated by one species: *Hyparhenia rufa*.

Soil samples from each horizon were taken from the soil profile at each harvest unit. The following information was recorded: average depth of each horizon, color (dry and wet), degree of compaction, consistency (wet and dry), hand texture, presence of roots, rocks, and gravel, permeability, apparent density, and infiltration capacity.

Samples were sieved in a 2-mm mesh, dried, and sent to the laboratory for physical and chemical analysis including texture, structure, organic matter content, bulk density, moisture retention curve, and total porosity (Figueroa et al. 1983). A recording rain gauge was installed at both watersheds.

Soil losses were measured in a calibrated drum and measurement commenced at all plots at the same time. The sediment collectors had a sediment trap to retain the coarser sediments. Measurements were performed daily or whenever a rainfall event occurred. Runoff volume, the amount of water in the metal collector, was recorded and a 1-liter stirred sample was taken to determine suspended sediment (fine particles) distribution. At the lab, sediment content from the samples was determined using the method described by Kunkle and Thames (1976) and Brakensiek et al. (1979).

Simulated rainfall

We conducted experiments with a portable rainfall simulator to evaluate the individual sediment production from each BMP applied in this study. This rainfall simulator was constructed at Utah State University and was used in Honduras at the study site to assess the effectiveness of the proposed BMPs. The simulator consisted of an oscillating module (made of plexiglass sheets) containing evenly spaced nozzles (hypodermic needles) placed at a height of 3 m from the soil surface. Rain falls from the raindrop-producing module over a 0.6 x 0.6 m runoff plot; runoff moves down through a trough and is collected in a bucket (Mutchler and Hermsmeir 1965). The rainfall simulator forms drops of approximately 2.5 mm in diameter and impacts the surface at about 70% of the terminal velocity, due to the effect of individual drop forming elements such as the hypodermic needles. These features are very important to reproduce the temporal and spatial variations of natural rainfall (Hall 1970; Meyer and Harmon 1979; Blackburn et al. 1974).

Each run lasted approximately 35 min at rainfall intensity of 60 mm/h to simulate a typical tropical storm. Runoff was collected and recorded every 5 minutes and water samples were taken to the laboratory for sediment content analysis. Sediment samples were oven-dried and weighed at the lab using the technique described by Kunkle and Thames (1976). Additionally, initial water content, soil bulk density, and soil compaction were recorded at each site. For each treatment, we ran five replicates and the average was used to plot an infiltration curve for each treatment.

Each BMP was individually tested. Timber harvesting experiments were conducted during the dry season of each year. For each experiment (*run*), the substrate

of the runoff plot was randomly selected in the harvest unit. The methodology used to run every simulation is described by Dobrowolski (1998).

Rainfall pattern

Rainfall amount, duration and intensity were determined for each storm over a 3 year period (1998-2000) (Figure 2-2). Annual precipitation regime has a monthly variation characterized by a bimodal rainfall pattern, where it has typically two peaks that divide the rainy season in two parts. The first part starts in late May or early June and ends in July or August. There is a short dry season of one or two months, then rain begins in August through October. September is the month with the highest precipitation, and these months are also the months of maximum flows. Essentially no significant rain events occur between November and May.

Rainfall intensities are also very high. Approximately, 95% of the rainfall is considered “erosive rain” (storm that exceeds 25.6 mm/h [Wishmeier and Smith 1978]). A 5-year study indicates that 50% of all rainfall events had a higher intensity than 20mm/h (Thurow and Smith 1998). Greater than half of Honduras might experience 300 mm of rain in 24 hours (Hargreaves 1992).

During the rainy season, measurements were taken mainly during the second half of the rainy season because most erosion problems occur later as soils become saturated. During October of 1998 extremely high rain events occurred due to hurricane Mitch. The erosion plots from this year were lost and replaced at the beginning of the next year.

Analysis

Sediment yield and runoff volume variables were analyzed using a Split Plot Design with the variable time nested within explicit repeated measures (SAS 1999) for the natural rainfall experiments. This design allowed us to detect differences between treatments (logging methods) throughout the rainy seasons of 1999 and 2000. Lower sediment production and runoff volume revealed the efficiency of one of the treatments. Comparisons of Means tests were performed to observe the differences between individual treatments against all others. Most data did not meet normality requirements and were log-transformed before the analyses. For the statistical analyses we used a significance level of $\alpha=0.05$.

We used a one-way Analysis of Variance (ANOVA) with 5 replicates for the simulated rainfall experiments to study differences among treatments.

This test detected differences between treatments (BMP, traditional) as class levels. We evaluated four treatments:

1. Harvesting (traditional-no BMPs)
2. Water bars (in skid trails)
3. Slash treatment (chop and scattering in a layer of 30 cm of harvesting residues)

4. No-harvesting (undisturbed forest)

The ANOVA tests were applied at the end of the simulations: for sediment yield and runoff volume and another test was applied the time runoff began.

Results

Sediment yield and runoff for 1999

Sediment yield reached its maximum value in September when the highest precipitation occurred (322 mm) (Figure 2-3) during the rainy season. The tractor-logged area reached an average sediment yield of 15,311 kg/ha (SD=14,708), while the cable-logged area yielded 1,490 kg/ha (SD=1,205). The highest sediment yields were produced during the month of July, reaching 459 kg/ha (SD= 411) for the tractor- and 99 kg/ha (SD=34) for the cable-logging treatments. During the rainy season, precipitation was lowest in July at 77 mm (Appendix, Table A-6). Despite the large variation between replicates, differences were statistically significant between treatments ($P=0.013$; Appendix Table A-1). The ANOVA results also showed significant differences between measurements among months ($P<0.001$; Appendix Table A-1) and among treatments (ANOVA; $P=0.002$; Appendix Table A-1). Sediment yield from tractor- and cable-logging was different over all months of the rainy season in watershed 1; clearly indicating that tractor logging produced more sediment than cable logging. Sediment yield increased as the monthly precipitation increased showing a significant difference throughout all months ($P<0.001$). Sediment yield increased as the rainy season developed and then decreased towards the end of the rainy season to the original starting point.

Runoff volume followed the same pattern as sediment yield. The highest runoff occurred in September in the tractor-logged area (Average=64.4 mm; SD=16.6), while the cable-logged area produced significantly less runoff during the same time period (Average=39.8 mm; SD=6.7) (Appendix, Table B-2). The month with the lowest runoff volume during the rainy season was July (Figure 2-4). Runoff volumes in the tractor-logged sites were significantly higher than in the cable-logged sites (ANOVA; $P=0.030$; Appendix Table A-2). There was also a significant difference among months of the rainy season (ANOVA; $P<0.001$; Appendix Table A-2); however, there was no interaction between treatments (cable and tractor) over the months of the rainy season (ANOVA; $P=0.112$; Appendix Table A-2).

There were also differences in runoff between the early rainy season and the late rainy season. A test of Differences of Least Squares showed that there were significant differences in runoff between July and September, July and October, August and September and September, and October ($P<0.001$). The other combinations did not show significant differences (July and June, and July and August).

Sediment yield and runoff for 2000

Tractor logging produced the largest amount of sediment, followed by cable logging. The tractor-logged treatment yielded nearly 1,846 kg/ha (SD=1,525) of sediment, while the cable-logged area yielded 320 kg/ha (SD= 184.2). Unexpectedly, sediment yield at the control plots was significantly higher than the animal-logging plots ($P<0.0001$). Animal logging reached only 146.4 kg/ha of sediment yield (SD=55.7), while the control plot

(undisturbed forest) reached 245 kg/ha (SD=153). Tractor logging produced more sediments and sediment yield increased as precipitation increased. Sediment yield reached its maximum value in September, the month with the highest precipitation (220 mm) (Figures 2-2) and 2-5). The lowest sediment yield for all treatments was during the month of October (Appendix, Table B-3). Sediment yield values were significantly different between all months ($P < 0.001$), and there were significant differences in all the interactions of treatments versus time during the three months of study ($P < 0.0001$). Statistical analysis showed significant differences among treatments (ANOVA; $P < 0.0001$; Appendix Table A-3) and for interaction between months and types of logging (treatments) (ANOVA; $P = 0.0004$; Appendix Table A-3).

Runoff volume followed a pattern similar to that of sediment yield in each of the treatments. Runoff peak occurred in September, the month of highest precipitation. BMP treatments produced significantly lower runoff volumes in all cases. The tractor-logged area had the highest runoff volume, reaching its peak in September (Average=16.5 mm; SD=9.9). The cable-logged site produced the next lowest runoff volume (Average= 8.2 mm; SD=0.8) followed by animal logging (Average=7.1 mm; SD=1.4). The undisturbed forest produced an average runoff volume of 8.4 mm (SD=2.2) (Appendix, Table B-4). The lowest runoff volume occurred in October (< 3 mm) (Figure 2-6).

Statistical analysis showed a significant difference in runoff volume among the types of logging systems (ANOVA; $P < 0.0001$; Appendix Table A-4). It also showed a significant difference among months of the rainy season (ANOVA; $P < 0.0001$; Appendix Table A-4), and there was an interaction between treatment and months (ANOVA;

$P=0.007$; Appendix Table A-4; Fig.2-6). There were also significant differences in runoff between August and September, August and October, and September and October ($P<0.001$).

Comparing the results with those of watershed 1, we observed that runoff volume was also higher at the tractor logging treatment, followed by cable logging and animal logging which had a runoff volume similar to an undisturbed forest. Runoff volume during this year was much lower than in 1999 in the first experiment, in watershed 1, and this pattern was consistent with the pattern for sediment yield. Even though the watersheds cannot be compared with each other, the control plots established in undisturbed forest areas reveal that the cable- and animal logging areas are similar to unlogged conditions in terms of runoff volume produced.

Infiltration rates using rainfall simulations

The slash treatment showed the highest infiltration rate during the simulations and was higher than the undisturbed forest (control) (Fig. 2-7; Appendix B; Table B-5). Slash treatment had an infiltration rate between 5.5 to 6 cm/h during the 35 minutes of the simulated rainfall. The infiltration rates of the other treatments: traditional harvest, water bars, and the undisturbed forest (control) plots were significantly lower (Fig. 2-7). Undisturbed forest sites (control plots) had the highest infiltration rate of these remaining treatments, followed by the water bar treatment. The treatment with the lowest infiltration rate was the traditional harvest method, which lacked water bars and slash treatment. For all treatments, there were significant different differences in sediment

yield (ANOVA; $P < 0.05$, $F = 17.3$; Appendix A; Table A-5) and runoff volume (ANOVA; $P < 0.05$, $F = 17.4$; Appendix A; Table A-5), at the end of the 35-minute simulations.

Accumulative and total runoff from rainfall simulations

The traditional harvesting method treatment showed the highest cumulative runoff followed by the water bar treatment (Fig. 2-8; Appendix B; Table B-5). Again, the control plots showed higher runoff volume than slash treatment. Slash treatment showed the lowest runoff volume during all simulations. There were significant differences in the time that runoff initiated in all treatments (ANOVA; $P < 0.05$, $F = 7.05$; Appendix A; Table A-5).

The control plots and the traditional harvesting plots produced the highest runoff volume. There were significant differences between the runoff volumes during all simulations (ANOVA; $P < 0.05$; Appendix A; Table A-5). The total runoff volume during the simulations exhibited the following order (from high to low): Control (undisturbed forest), traditional harvesting, water bars and slash treatment (Fig. 2-8; Appendix B; Table B-6, summary).

Discussion

Alternative harvest methods significantly decrease the amount of sediment and runoff from timber harvest sites. When using alternative methods such as harvesting with cable or animals, sediment yield can be almost as low as the natural erosion rate in an undisturbed forest. These results are very consistent with other studies in Central America and differ little from the results found in the Western United States. In general, the erosion rate in tractor-

logged areas was six to ten times higher than the erosion produced by cable logging. Numerous research studies and published papers have documented high erosion rates resulting from tractor logging (Satterlund 1972; Megahan 1980; Clayton 1980; Seyedbagheri 1996). Cable systems (high-lead and skyline) reduce soil removal and erosion because logs are either partially or fully suspended above ground thus creating less soil disturbance (Smith after Seyedbagheri 1996) found that skyline systems had an average of 10% disturbed area. Similar results were found by Cromack et al. (1978), where high-lead systems produced less than half of the erosion produced by a typical skidder tractor-logging operation. Tractor logging displaces more soil than the other logging systems, thus the use of tractors should be minimized. When tractor use is unavoidable, tractor size should be minimized.

Results also showed that the erosion rate in timber harvesting activities varies greatly. This variation can oscillate from 30 kg/ha to 15,000 kg/ha, depending mainly on the hydrological year as well as the soil and geology type. Comparing the two watersheds, we noticed that there was a large variation in sediment yield between watersheds, even though they were only 4 km apart. This difference can also be attributed to the difference in amount of precipitation between the study years (1999 and 2000), indicating that there is a large variation in precipitation between hydrological years (Fig 2-2). Seyedbagheri (1996) also found these large discrepancies among studies conducted in the United States.

The undisturbed forest plots had a significantly higher erosion rate than the animal plots. The undisturbed plots were located at the lower part of the watershed (Fig. 2-1) with a

50-m difference in elevation. The lower watershed was subjected to 20% higher precipitation intensity. Since the precipitation in this area has an orographic origin, upper watersheds received lower intensity precipitation (cloud forest) than lowland watersheds. We had an experimental design that had a confounding effect in space and we assumed that all plots responded similarly to seasonal rainfall variations suggesting that differences were due to treatments. However, it was very difficult to locate the unharvested plots somewhere nearby the treated harvested units due to forest management prescriptions and logistical constraints. For this reason, we had these unexpected results.

The results of these timber harvesting experiments also showed that both the cable and the animal logging systems were low-impact. In Honduras, where the erosion hazard is high, animal logging systems may be an appropriate alternative harvest method.

These results are also consistent with other animal logging studies which suggest that animal skidding also disturbs less soil than tractor skidding, resulting in little site disturbance (Satterlund 1972; Studier et al. 1984; FAO 1989).

The simulated rainfall experiments revealed two important things. First, slash treatment appears to be the best treatment for a harvested area because it reduces sediment yield and increases infiltration (and also keeps the nutrients in the harvested area). Slash treatment also provided the best protection for water quality. These results are similar to investigations conducted in the US (New Mexico State Forestry 1990; Montana Division of Forestry 1994), in Mexico (Alcala et al. 1998) and Costa Rica (Wallin and Harden 1996). Second, the use of water bars diffuses runoff and retains sediments being produced either at the road or skid trail. These physical barriers produce

a great deal of sediment due to excessive soil removal during their installation; however, they should be seen as sediment catchment practices that avoid soil particles being diverted into water bodies. Their use is recommended only when they are installed along with other practices such as slash treatments, mini-check dams and rock or log barriers. Similar recommendations have been made for harvest units and skid trail treatments in the US (Seyedbagheri 1996; US Forest Service 1983). Traditional tractor harvesting without slash treatment and water bars should be avoided if possible or minimized.

Runoff and infiltration rate findings revealed the unique hydrological conditions of most upper pine-forested watershed in Honduras. Their hydrological behavior was quite different from other temperate watersheds. Rainfall was high, the consequent runoff and the vegetation cover were dominant components of the hydrological cycle. The ground was usually covered by leaves, stems, branches, and wood. As a consequence, when it rained, the water was held by the vegetation and had a greater chance to infiltrate.

Due to these conditions, subsurface flow was generally significant. In our study watersheds, runoff represented less than 15 to 25% of the precipitation. Monthly runoff volume varied from 8 to 50 mm, while the monthly precipitation varied from 62 to 322 mm. In addition, these experiments showed that even when the runoff is high in an undisturbed forest, the sediment content is much lower than other disturbed areas. This demonstrated the high capacity of these watersheds to produce runoff, but retain sediment under natural conditions (Hudson et al. 1983). Increased infiltration and reduced runoff volume produced a constant aquifer recharge, reducing water quality impairment and

controlling flood damages downstream (Hargreaves 1992). Aquifers being recharged during the rainy season provide water for base flow during the dry season.

Tropical rainfall usually consists of raindrops that have more kinetic energy than temperate rainfall to detach and transport larger soil particles. During rainfall events, unprotected slopes can be easily eroded by the energy of rain and the detached particles removed via runoff (FAO 1989). In harvested/disturbed watersheds, it is important to maintain adequate ground cover (Cromack et al 1978). The lack of cover during the onset of the annual rainy season can lead to severe erosion in forest lands. Trees, vegetation, and ground cover provide a good protective cover against soil erosion and sedimentation.

Conclusions

Traditional tractor logging methods in the pine areas of Honduras without the implementation of BMPs creates extreme runoff and erosion hazards. Our results are similar to those found in the western United States; however future research is needed to support development of improved logging techniques. Prior to this study, we could find no studies that were conducted in the tropics at a field-scale resolution. Data from control watersheds could provide more reliable information about erosion processes, which account for most of the observed erosion. These data would also provide more realistic information about soil loss and runoff processes occurring at the pine-forested watersheds.

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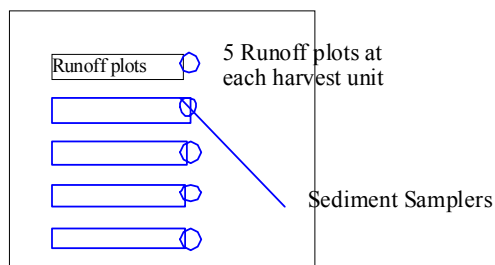
Experiment Layout

Timber Harvesting

Design of each Harvest Unit

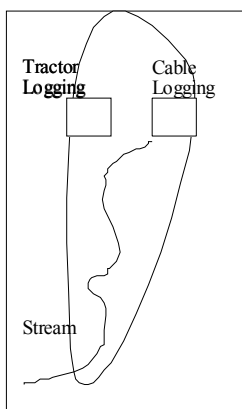
4 Harvest Units:

Cable logging
Tractor logging
Animal logging
Natural Forest



Watershed Layout & Treatments

Watershed 1 (1999)
Layout of Harvesting Units



Watershed 2 (2000)
Layout of Harvesting Units

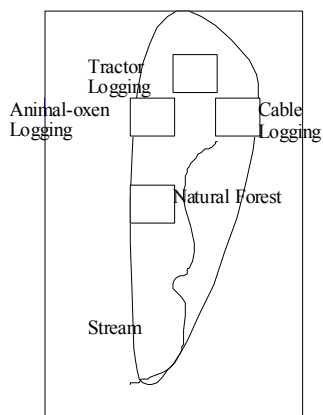


Fig. 2-1. Layout of the timber harvesting experiments

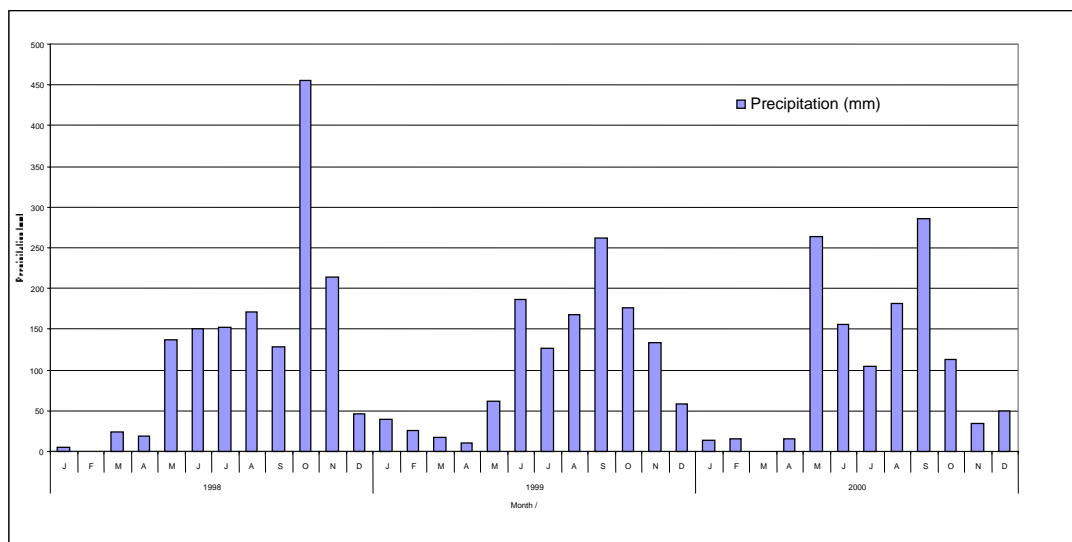


Fig. 2-2. Monthly rainfall from 1998 through 2000, Siguatepeque, Honduras.

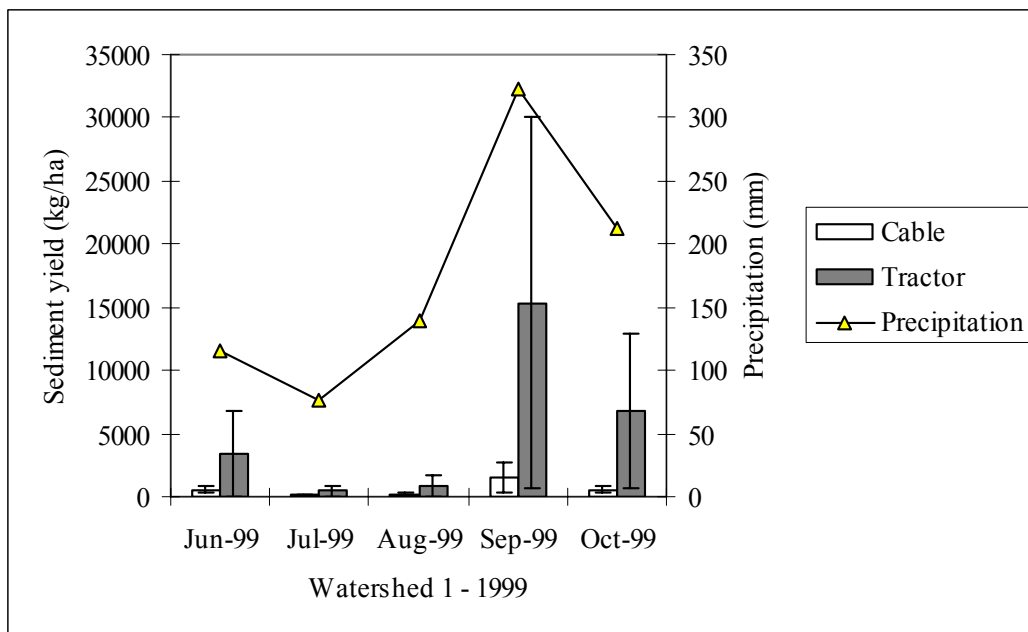


Fig. 2-3. Sediment yield from different logging systems in Watershed 1-1999. The logging methods are: cable logging and tractor logging.

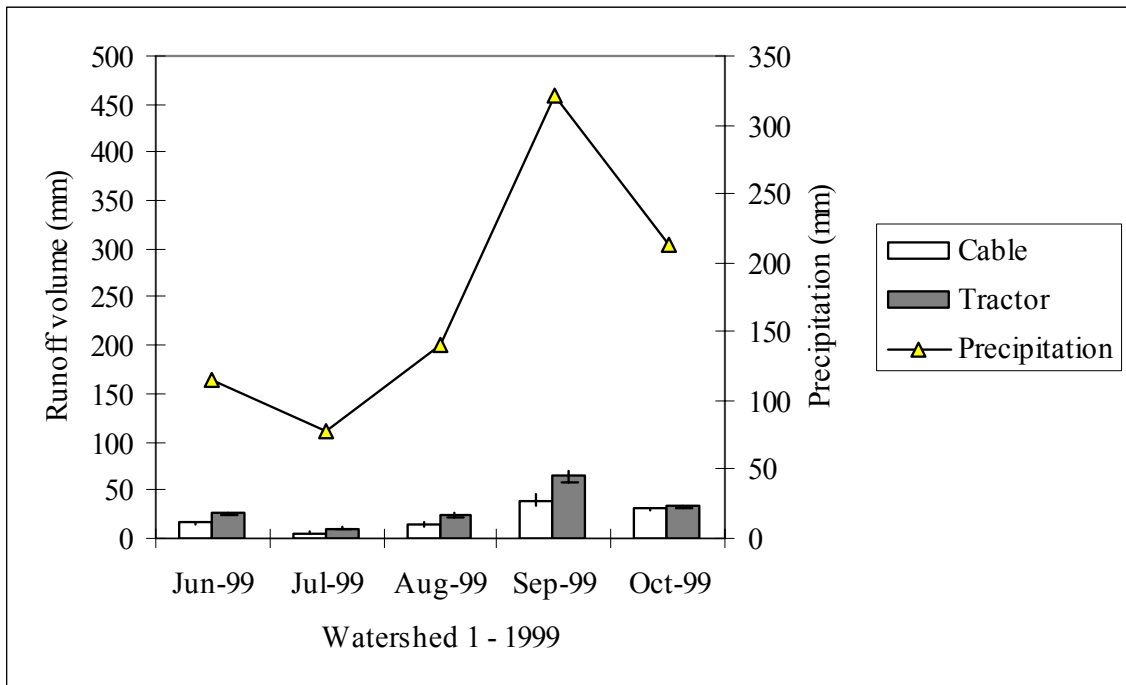


Fig. 2-4. Runoff volume from different logging systems in Watershed 1-1999. The two different methods are: cable logging and tractor logging.

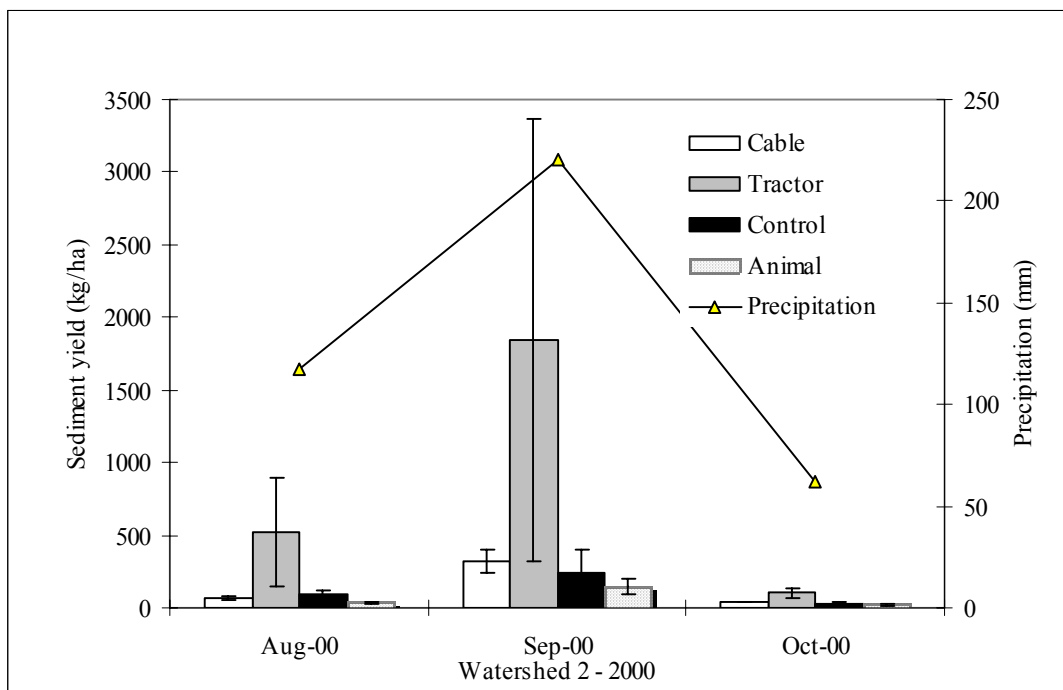


Fig. 2-5. Sediment yield from different logging systems in Watershed 2-2000. The three different methods are: cable logging, tractor logging, and animal logging. Erosion in a natural, undisturbed forest (control) is also compared with the three treatments.

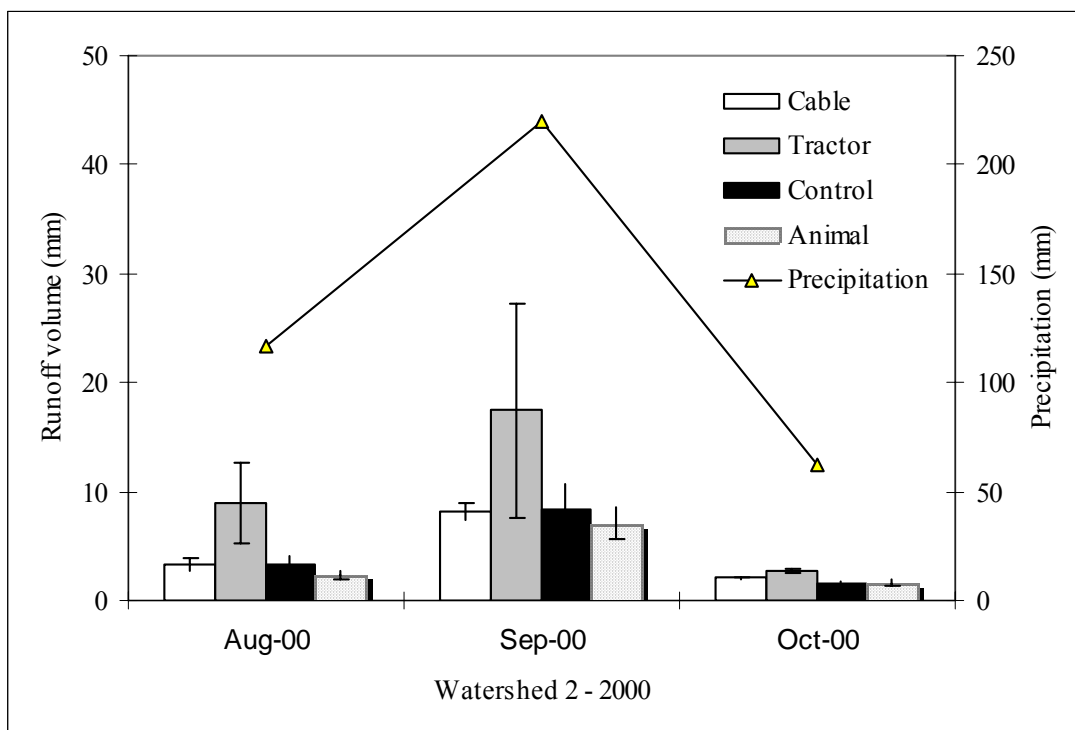


Fig. 2-6. Runoff volume from different logging systems in Watershed 2-/2000. The three different methods are: cable logging, tractor logging, and animal logging. Erosion in a natural, undisturbed forest (control) is also compared with the three treatments.

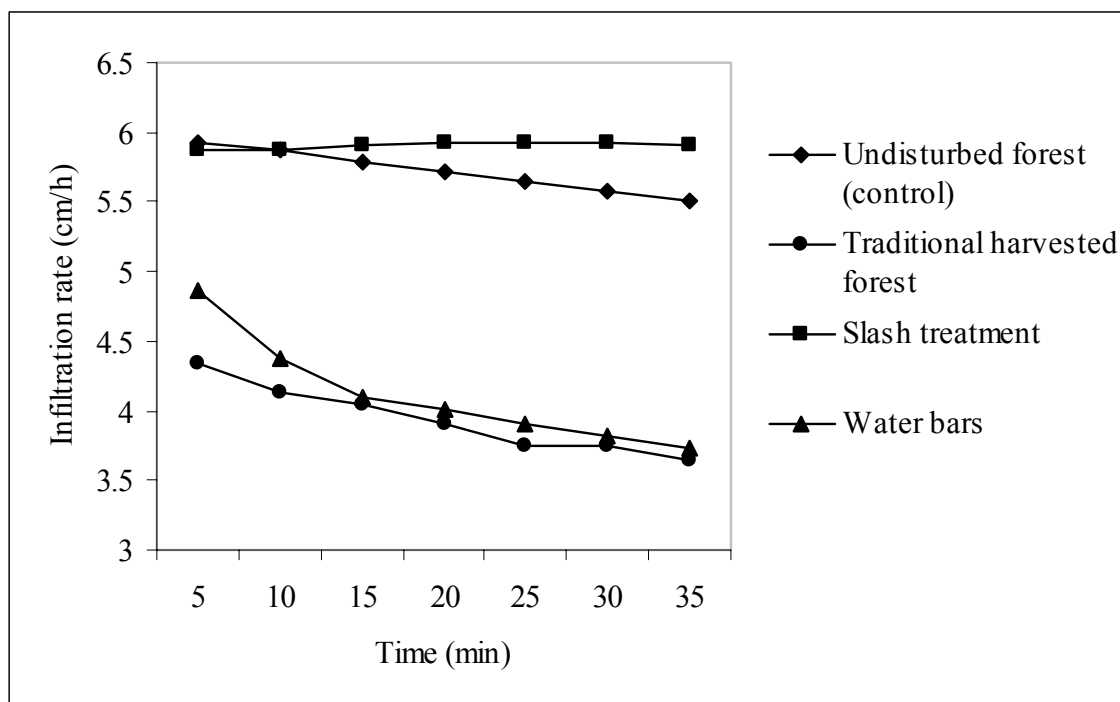


Fig. 2-7. Infiltration curves from different harvested scenarios using simulated rainfall. Infiltration rate in a natural, undisturbed forest is also compared with the three treatments: traditional harvested forest, slash treatment, and water bars.

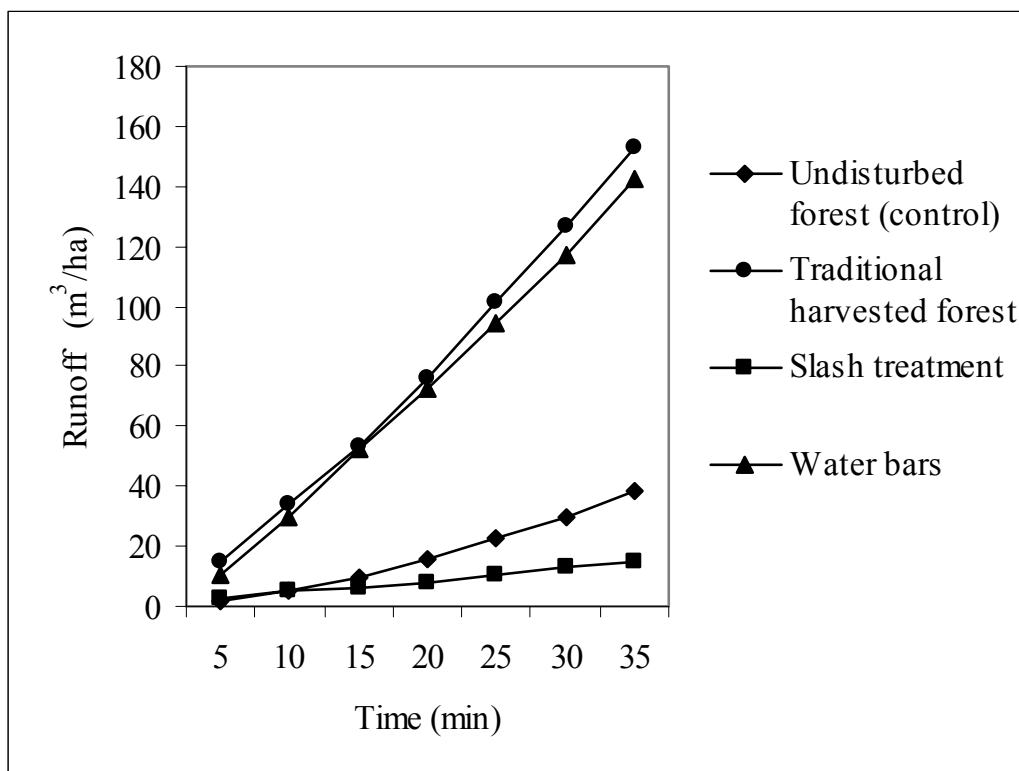


Fig. 2-8. Accumulative runoff volume from different harvest scenarios using simulated rainfall. Accumulative runoff volume in a natural, undisturbed forest (control) is also compared with the three treatments: traditional harvested forest, slash treatment, and water bars.

CHAPTER 3

TESTING ROAD BEST MANAGEMENT PRACTICES IN HONDURAS²**Abstract**

Forest roads produce more erosion and sedimentation than any other forest or agricultural activity. In central Honduras, soil losses were evaluated for two years on two parts of a forest road: the road surface and cut and fill slopes. We divided a 400-m segment of road into eight 50-m long experimental units. Four units were treated and four were left untreated. In the first year (1999), the treatments included reshaping of the road prism, installation of culverts and reshaping of road ditches, compaction of 20-cm layers of the road tread, crowned surface (3% slope, double drainage) and a longitudinal slope less than 12%. A layer of gravel (10 cm, crushed at 0.63 cm = 1/4 inch) was added to the treated road segment in 2000. Control road segments were left untreated.

Revegetation measures (BMPs) were implemented to control erosion on the cut and fill slopes. *Hyparhenia rufa* and *Vetiver zizanioides* were used as re-vegetation grasses in the first and second years, respectively. *Hyparhenia rufa* proved to be very effective in reducing up to 90% of the sediment produced. Unvegetated road slopes produced nearly 40,000 kg/ha/year of sediments while revegetated road slopes produced

2. Coauthored by Samuel Rivera and Jeffrey L. Kershner

only 3,000 kg/ha/year.

However, the second grass showed no significant difference between the revegetated and unvegetated plots. This outcome might be the result of the result of the due to differences between the propagation methods of these two grass species and to the late establishment of the second grass species.

Introduction

The majority of sediment production from forest management comes from timber harvest and road building. The construction and maintenance of forest access roads alone is responsible for more than 90% of sediment produced during logging operations (Brooks et al. 1991; Sidle 1980; Megahan 1980). FAO (1989) found that the sediment production from a road (4-m width, 10%-average slope, 6 culverts/km, and 3,900 mm of precipitation/year) could be as much as 500 ton/km/year depending upon traffic intensity. The rate of coarse and suspended sediment production for an unsealed road surface ranges from 6 to 10 and 14 to 26 ton/km/year respectively (Gray and Sotir 1996). Both coarse and fine particles may settle in adjacent water bodies, resulting in the sedimentation of stream channels and reservoirs, and the deterioration of water quality.

Sediment production at the forest road prism occurs at three critical features: the road surface, cut slopes, and fills slopes. At the road surface, unconsolidated road surface material is susceptible to erosion during precipitation events and may have erosion rates up to 21.5 times higher than that of timber harvest areas (Burroughs and King 1989). The annual sediment production from forest road surfaces is from 125 to

225 tons/km/year; two thirds is suspended sediment and the rest is coarse material (Gray and Sotir 1996). Road cuts decrease road stability by mechanically steepening and undercutting natural slopes (Megahan et al. 1984). They cause significant amounts of erosion and sedimentation to adjacent streams and other water bodies (Sedyedbagheri 1996; FAO 1990; Sidle 1980). Road cut erosion rates may be as high as 40.4 tons/ha/year (Burroughs and King 1989). Road fill failures are the highest source of sediment from forest roads (FAO 1989). Erosion rates from road fills can reach 1.27 cm/year (Sedyedbagheri 1996) and are triggered when the shear stress on slope soils becomes higher than the shear strength of the soil (FAO 1989).

Best Management Practices (BMPs) are techniques developed to prevent or reduce water pollution from non-point sources (US Forest Service 1983). The most common road BMPs include: buffer strips along stream channels, installation of water bars on skid trails, revegetation of disturbed areas (fills and cuts), filter windrows on fill slopes, adequate surface and subsurface drainage structures, proper low impact logging systems, management of harvesting residues, and proper location and design of all haul roads (Lynch et al. 1985; Logan 1993; US Forest Service 1983). Revegetation of cut and fill slopes and gravel surfacing are the most common treatments to reduce erosion at the cut and fill slopes and road surface. Revegetation protects cut and fill slopes against the erosive effects of rainfall. This vegetative cover intercepts rainfall drops, reducing soil detachment and raindrop splash. At the same time, the velocity of runoff is reduced by increasing slope roughness and soil porosity. Infiltration capacity is therefore increased (Gray and Sotir 1996).

Gravel surfacing has proven to be a very effective tool to protect road surfaces. A properly graveled road surface produces less sediment than an unsealed road surface because an increase in surface roughness reduces raindrop impact and soil particle detachment. Surfacing with durable materials and compaction with blading (grading) are effective techniques to reduce the amount of small soil particles produced on a forest road surface (US Forest Service 1993). An adequate thickness of surface gravel (7-10 cm) must be used to ensure durable protection.

The 7,000 km road network in Honduras produces large amounts of sediment. In 1998 only 20.3% of the roads were paved (World Bank 2001). The unpaved roads are characterized as low-traffic roads constructed in steep mountainous terrain with unconsolidated material. These roads are used mainly to connect small villages and to provide transportation for products, especially coffee and timber. There are no specific regulations for protecting water quality during road construction and maintenance. In most cases, water quality protection is ignored by the forestry technicians and private companies. There are no regulations for slope protection nor are there standards for the construction and maintenance road surfaces or drainage. Currently, there is no protection for streamside zones, riparian areas, and municipal watersheds during road construction (Laboranti 1992).

The general objectives of this study were to determine and compare soil loss from treated (BMP implemented) and untreated sites (traditional road construction practices) during and after forest road construction and to determine the erosion rates from cut and fill slopes treated with revegetation measures.

Study Area

This study was conducted in the pine forests of the National School of Forest Sciences (ESNACIFOR) (Figure 3-1), located 3.5 km to the southwest of the town of Siguatepeque, Honduras. The school forest has 42 km of roads that connect the area of 4,200 ha. This road system is used for all the forest management activities such as timber harvesting, reforestation, and fire protection. The school forest area is located within the El Cajon watershed which supplies the nation's largest reservoir and is the source for 70 percent of the country's hydropower (Gollin 1994). The area is very mountainous with elevations ranging from 540 to 2,500 m above sea level. Most of the forest is located on slopes greater than 40%. The soils are well-drained Lithosols of the series Cocona with a sandy loam texture and a pH ranging from 5.0 to 6.0 (Simmons and Castellanos 1969). Honduras is a rich country in terms of natural resources and has the highest percentage of forest lands among the other Central American nations (Humphrey 1997; Campanella et al. 1982; COHDEFOR 1996). Approximately, 50% of the country is still covered by forests (Rivera 1998), which include humid tropical forests, arid or deciduous tropical forests, cloud forests, mangrove wetlands, and pine forests (Humphrey 1997; Rivera. 1998). Tropical forests are typically associated with coastal mountains receiving high amounts of precipitation while pine forests are located in the headwaters of rivers in the mountains of central Honduras.

Methods

We designed two studies to evaluate the soil loss from road surfaces and cut and fill slopes. To test BMP effectiveness of the road surface treatment, we divided the road into eight 50-m long segments; four segments using BMP methods (treated) and the other four located on a road section where traditional road construction methods were used (see Figure 3-2).

We used the following BMPs during the first year of study: (1) reshaping of the road surface; (2) installation and cleaning of existing concrete culverts; (3) compaction in two 20-cm layers of the road tread with selected material where the surface was crowned to 3% slope with (double drainage: (outslope and inslope surface)); (4) improvement and reshaping of road ditches (1-m width and 0.5-m depth); and (5) longitudinal slopes less than 12% (all road segments range between 8 and 12% slope).

Prior to the first measurement period, all road sections (BMP and traditional) were graded to remove wheel ruts and provide a consistent initial road condition. The control reach was located adjacent to the BMP segment in the untreated part of the access road. Both traditional and BMP sections were measured under similar traffic conditions. Traffic was estimated with a traffic counter at a rate of 2,400 vehicle passes per year, including 30% heavy trucks and 70% medium and small vehicles. Vehicles speeds rarely exceed 45 km/h. Soil losses were measured using a rillmeter (cross section lowering measurement) (Seyedbagheri 1996). Each 50-m road segment was divided into three equal sections and measured at the end of the first and second third of each segment (Blaney and Warrington 1983). Two measurements (34 readings each) were made in each of the eight 50-m long road segments. Cross section locations were marked with

buried concrete benchmarks. Rills were measured daily during the rainy season. The rillmeter not only measures soil losses, but also soil depositions along the road. For the purpose of this study, soil deposition was also considered as a soil loss because this represents unconsolidated soil particles that will eventually leave the road surface through the road drainage system, producing erosion and sedimentation.

There were no road surface treatments (sealing) in 1999. In 2000, a road tread surface treatment was added to the treated road segments. This treatment consisted of a layer of 10 cm of gravel (washed and crushed at 0.63 cm = 1/4 inch). Eighty cubic meters of gravel were hauled to the study area and were uniformly distributed along the treated road surface using a grader.

Two different types of grasses were used to seed road cuts and fills. In 1999, we revegetated the fill and cut slopes using a native grass, *Hyparhenia rufa*. In 2000, we used an exotic grass species (*Vetiver zizanioides*). *Hyparhenia rufa* has proven to be very adaptable and tolerant to droughts and fires and is effective in reducing erosion. Its use has been promoted by US AID and the US Forest Service for use in hillslope stabilization projects in Guatemala and Bolivia (Keller 1997). The roots of *Vetiver zizanioides* have also been shown to be effective in retarding hillslope erosion. They can go into the ground up to 3 m and when planted on barriers can form terraces of up to 4 m high. The UN Food and Agriculture Organization (FAO 1988) has promoted its use worldwide in tropical nations.

Cut and fill slopes that were previously constructed were reshaped with the grader blade. Four cuts and the same number of fills (with uniform grade) were randomly

selected for this experiment (Fig. 3-2). Within each fill and cut, one half was revegetated and the other half was left as a control. Revegetation was conducted at the beginning of the respective rainy seasons of the study period. *Hyparhenia rufa* was seeded over the treated slopes and covered with timber harvest residues to reduce rainfall impacts and reduce the risk of seeds being washed away during the first storms. *Vetiver zizanioides* was propagated by root division and slips. The slips were planted at 15-20 cm intervals and buried 5 cm deep in a line along the contour, angled slightly uphill (Leonard 1992). In each experimental unit a 1 x 1 m-runoff plot was established at the bottom of the slope (Grace 2000). Daily measurements of runoff volume were conducted during the rainy seasons. A previously stirred 0.5-liter water sample was taken to the lab to determine sediment content. Sediment samples were oven-dried and weighed at the lab (Kunkle and Thames 1976; Brakensiek et al. 1979).

Additional information was recorded at each site including: average depth of each horizon, color (dry and wet), degree of compaction, consistency (wet and dry), hand texture, presence of roots, rocks, and gravel, permeability, bulk density, and infiltration capacity. Soil samples were sieved in a 2-mm mesh filter, dried, and sent to the laboratory for physical and chemical analysis which included texture, structure, organic matter content, apparent density, moisture retention curve, total porosity, nitrogen, phosphorus, potassium, soluble ions, pH, and electric conductivity (Figuroa et al. 1983).

Analyses

We used a Split Plot Design with *time* (months) nested within explicit repeated measures to detect differences between treatments throughout the months of the rainy season. Most data were log-transformed to meet normality assumptions. A generalized linear model procedure (Proc GLM, SAS 1999) was used to analyze the data. A test of Differences of Least Squares Means was used to detect differences among all months while Comparison of Means tests were used to detect the differences between individual treatments. We used a significance level of $\alpha = 0.05$. A summary of the field data is reported in Appendixes B-1 to B-4.

Results

Soil losses and deposition on the road surface 1999

Unprotected (control) road surfaces produced twice as much as sediment the BMP-treated road. Due to the large amount of rainfall, some sloughing within the untreated road segment contributed to the much higher soil loss. When observed annual soil loss was plotted by month, it became obvious that BMP treated road segments produced low soil loss during the study period. The highest soil loss occurred in September for both the control road (average = 230 m³/km; SD=76.7) and the BMP road (average = 128.5 m³/km; SD = 42.3) (Fig.3-3). Soil loss was lowest in July (control road average = 41.5 m³/km, SD=23; BMP road = 10.5 m³/km, SD = 11.2). There was a significant difference in sediment production between the treated and untreated road segments (ANOVA; P=0.019; Appendix Table A-6). There was also a significant difference in sediment production between the 4 months of the rainy season (ANOVA;

$P < 0.001$; Appendix Table A-6). Significant differences occurred between treatments for all months ($P < 0.001$), except for August and October ($P = 0.2974$). Sediment yield increased as the rainy season developed, and then it decreased toward the end of the rainy season to the same value at the beginning (August).

Soil deposition consisted of soil particles eroded from the road surface which were moved along the road. These soil particles are deposited into the road ditches and are finally transported to a given point within the watershed. Soil deposition increased as the rainy season developed and then decreased toward the end of the rainy season to the same value as at the beginning (August). Soil deposition values for the rainy season of 1999 were slightly lower than the values for both the control and the BMP road (Fig. 3-3).

The highest soil deposition occurred during September and the lowest in July. There was no difference between treatments (ANOVA; $P = 0.0687$; Appendix Table A-7), but there was a significant difference in the soil deposition values for the 4 months of the rainy season (ANOVA; $P < 0.001$; Appendix Table A-7). There were also significant differences among all months ($P < 0.001$), except for the sediment yields of August and September, and August and October ($P = 0.2974$). There was no interaction between treatments and months (ANOVA; $P = 0.598$; Appendix Table A-7).

Soil loss and deposition on the road surface 2000

In 2000, a single BMP (10-cm of gravel) was applied to the treated road while the control road remained untreated. No significant differences were found between treatments

for soil loss or for soil deposition (ANOVA; $P=0.352$; Appendix Tables A-8 and A-9). The highest soil loss at the control road occurred in September (average= $158 \text{ m}^3/\text{km}$; $SD=82.9$), while the BMP road produced an average of $116 \text{ m}^3/\text{km}$ ($SD=55.4$) (Appendix, Table B-8) (Fig.3-4). The lowest amount of soil loss occurred in August (control road average $73.5 \text{ m}^3/\text{km}$, $SD=46.7$; BMP road average $95 \text{ m}^3/\text{km}$, $SD = 62.3$). There was no difference between treatments (ANOVA; $P=0.352$; Appendix Table A-9). There was a significant difference in the amount of soil loss among the 3 months of the rainy season (ANOVA; $P=0.013$; Appendix Table A-9), but there was no interaction between treatments and months (ANOVA; $P=0.726$; Appendix Table A-9). There was no significant difference between August and October ($P=0.513$) but there was a significant difference between September and October ($P=0.022$).

Soil deposition was slightly lower than soil loss for both the control and the BMP road in 2000 (Fig. 3-4). The highest rate of soil deposition occurred in the month with the highest precipitation (September) and the lowest occurred in the month with the lowest precipitation (October). There was no difference between treatments (ANOVA; $P=0.725$; Appendix Table B-5), but there was a significant difference between the values of soil deposition during the 3 months of the rainy season (ANOVA; $P=0.013$; Appendix Table A-7), while there was no interaction between treatments and months (ANOVA; $P=0.598$; Appendix Table A-7).

Sediment yield from cut slopes (1999)

Untreated cut slopes contributed to extremely high soil loss during the study

period. Sediment yield from non-revegetated cuts was 10-20 times higher than the revegetated ones with *Hypparhenia rufa*. More sediment yield was produced in September than in any other month for both the revegetated (mean = 1,477 kg/ha; SD=2,076) and the control sites (mean = 23,380 kg/ha; SD=10,324). July was the month with the lowest precipitation during the study period. The lowest sediment yield for both the treated (mean= 214 kg/ha; SD=137) and the untreated units (average= 3,135 kg/ha; SD=2,369) (Fig. 3-5; Appendix Table B-9) occurred in July. There was a significant difference between the sediment yield at the control plots and the revegetated plots (ANOVA; P=0.001; Appendix Table A-10) (Fig.3-5). Sediment yield from cut slopes increased as the precipitation increased during the rainy season (among months) (ANOVA; P=0.001; Appendix Table A-10). There was also an interaction between time and treatments (ANOVA; P=0.105; Appendix Table A-10), with significant differences between all treatments - months (P<0.001) for the four months of the study (P<0.0001).

Sediment yield from fill slopes (1999)

The erosion from the control (bare ground) fill slopes was also 10-20 times higher than the erosion produced by the revegetated cut slopes with *Hypparhenia rufa*. September was the month with the highest precipitation (284 mm), producing the highest sediment yield for both the revegetated (mean= 743.2 kg/ha; SD=620.54) and the control unit (mean = 22,520 kg/ha; SD=6,434.5). July was the month with the lowest precipitation during the study period and thus showed the lowest sediment yield for both the treated and the untreated units (Fig. 3-6; Appendix Table B-9).

Sediment yield from non-revegetated fills was higher than the revegetated fills and sediment yield increased as the precipitation increased during the rainy season. There was a significant difference between the revegetated and non-revegetated fill slopes (ANOVA; $P=0.004$; Appendix Table A-11). Sediment yield produced during the months of the rainy season increased to a peak in September and then decreased to the end of the rainy season (ANOVA; $P<0.0001$; Appendix Table A-11). There was a significant difference for interaction between months and treatments (ANOVA; $P<0.0001$; Appendix Table A-11).

Sediment yield from cut slopes (2000)

Vetiver zizanioides tested in 2000 proved to be less effective in retaining soil particles than *Hypparrhenia rufa*. Sediment yield decreased during the rainy season, which differed greatly from the sediment yield observed in 1999 (Fig.3-6). August was the month with the highest sediment yield. The values for sediment yield were 12,536 kg/ha (SD=8,590) for revegetated treatments and 13,934 kg/ha (SD=9,185) for bare soil. October had the lowest precipitation during the study period, producing the lowest sediment yield for both the treated and the untreated units (Fig. 3-7; Appendix Table B-10).

In contrast to our results for the cut slopes in 1999, the erosion from the control (bare soil) cut slopes was similar to the erosion produced by the revegetated cut slopes. There were no significant differences between revegetated and non-revegetated fill slopes (ANOVA; $P=0.510$; Appendix Table A-12). While September was the month with the

highest precipitation (199.5 mm), more sediment was produced in August even though the precipitation was only 25% (69 mm) of the total amount of rain in September. There was a significant difference in the sediment yield produced between months during the rainy season (ANOVA; $P=0.008$; Appendix Table A-12) and no significant difference for the interaction between months and treatments (ANOVA; $P=0.802$; Appendix Table A-12). There were also significant differences between the erosion produced at the beginning and at the end of the rainy season (August-October, $P=0.006$), while no significant differences were found between September and October ($P=0.168$).

Sediment yield from fill slopes (2000)

Sediment yield also decreased during the rainy season at fill slopes. August was the month with the highest sediment yield for the revegetated fill slopes (average=8,842 kg/ha; SD=2,828), even though September was the month with the highest precipitation. However, for the control units (bare soil), September showed the highest erosion (mean = 12,688 kg/ha; SD=4,304) (Fig. 3-8; Appendix Table B-10). There was no significant difference in sediment yield for the revegetated and non revegetated fill slopes (ANOVA; $P=0.197$; Appendix Table A-13), but there was a significant difference in sediment yield during months of the rainy season (ANOVA; $P=0.002$; Appendix Table A-13). There was no significant difference for the interaction between months and treatments (ANOVA; $P=0.171$; Appendix Table A-13).

Discussion

Road surface erosion can be reduced up to 50% with the implementation of BMPs

that increase road base compaction and improve water movement over the road surface. Gravel surfacing has proven to be a very effective tool to protect road surfaces (US Forest Service 1993), but this treatment, besides its high cost, did not prove to be very effective in reducing erosion on this type of road (low volume and low traffic forest roads). This might be attributed to the short study period and the fact that the road surface was already compacted so that little soil particle movement occurred at the road surface. We also assumed that measuring the road surface with the rillmeter may not be appropriate after applying a 10-cm layer of gravel because the rillmeter's pins may go into the interstitial spaces of loose gravel and measurements may not be accurate. Runoff plots might be a better method of measuring road surface treated with gravel. In general, we believe that the BMPs tested during the first year of experiments (1999) should be enough to protect the road surface, as long as they are properly implemented.

Fill and cut slope erosion can be reduced up to 90% when they are seeded immediately after construction. These data are consistent with the literature (FAO 1989; US Forest Service 1993). In the road slope experiments for cuts and fill slopes, *Hypparhenia rufa* proved to be very effective in reducing sediment yield, while *Vetiver zizanioides* did not show any reduction in sediment yield. This difference might be due to the propagation method. *Hypparhenia rufa* is a native grass whose seeds were spread over the treated area was covered with harvesting residues (leaves, twigs and branches). *Vetiver zizanioides* was propagated by root division and slips which were buried 5 cm deep in a line along the contour. Soil removal due to this form of planting might have been the cause of the recorded-high sediment yield. In fact, *Vetiver zizanioides* showed a

descending pattern in sediment yield throughout the rainy season, instead of a typical bimodal pattern where the highest sediment yield occurs in September, the month with the highest precipitation.

Sediment yield values were very similar to the ones found in the literature on the Southeastern US (Grace 2000) and most were higher than for the western US (Helvey and Fowler 1978). For instance, Grace (2000) found sediment yield values of revegetated slopes were between 4,700 kg/ha/year and 13,200 kg/ha/year, and 37,000 kg/ha/year in non-revegetated slopes. In this study, for non-revegetated slopes the sediment yield varied from 40,000 kg/ha/year in the first year to approximately 20,000 kg/ha/year during the second year. Revegetated slopes using *Hypparhenia rufa* produced approximately 3,000 kg/ha during the first year, while *Vetiver zizanioides* had a sediment yield of 16,000 kg/ year. This result is also consistent with Tollner et al. (1977) and Seyedbagheri (1996).

Interpreting the results of soil deposition on forest roads may be confusing. Soil loss is often referred to as erosion and the gain or deposition is also referred to as sedimentation. Erosion is the soil movement produced by the effect of raindrops or overland flow (in the case of water erosion) and sedimentation refers to the past deposition of soil particles at a given drainage reference point (Megahan 1984). In this study, the relationship between soil erosion and deposition was observed throughout the two years of study. Most soil erosion from the road surface occurred when there was more precipitation while soil deposition did not show the same relationship. The highest soil erosion occurred in September, while October was the highest month for deposition.

Because soil losses are slightly higher than soil deposition, it is assumed that the difference left the road surface through road ditches. This might account for the difference between soil loss and soil deposition. By October, soil was found down the slope and deposited along the road. For both soil deposition and soil erosion the variation did not have anything to do with the treatments and it was probably due to differences in seasonal precipitation.

In general, the testing of the above mentioned BMPs indicated that compaction of the road surface; road drainage system and revegetation of the road cuts were the most important practices to reduce soil erosion. Compaction and shaping (crowned surface) of the road prevent water from penetrating the road surface which reduces water ponding and allows for the dispersal of surface water. Road drainage protects the road configuration by dispersing concentrated flows that are associated with high water erosion and transport. This may be critical in controlling surface flows during high-intensity rain events in the tropics. Vegetation in the road cut slopes provides a good protective cover against splash erosion produced by heavy rain drops. The combined effect of the above mentioned BMPs proved to reduce erosion by almost half.

Long term studies should explore how far down the slopes soil particles are moving. The Sediment Delivery Ratio (SDR) is the ratio of sediment or soil delivered at a given point in the watershed coming from all upland sources above that point (Lal 1975). At the watershed scale, sediments from recently constructed roads are increased by a factor of five times while at the construction site they are increased by a factor of about 500 times (Seyedbagheri 1996). This indicates that there is a slope storage of

sediments along the hillslope profile and the road. We assumed that the percent of sediments reaching stream channels might be very low with the implementation of the tested road BMPs (reducing half of the produced erosion). The SDR may provide that exact amount of sediment that reaches the down slope water resources.

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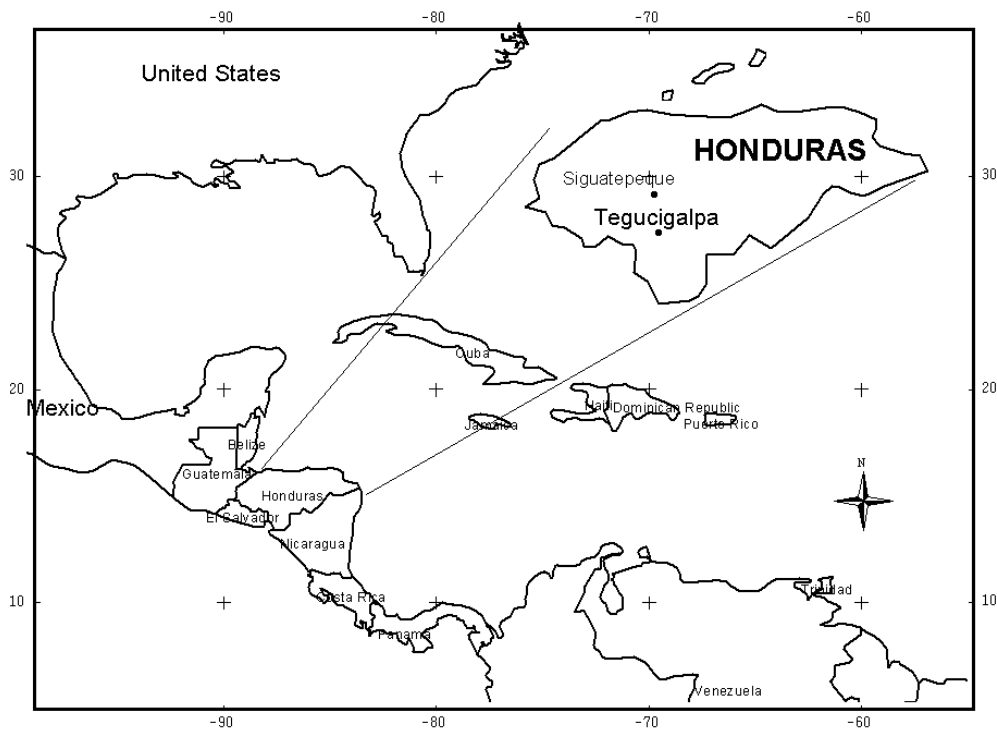


Fig. 3-1. Location of study site in Siguatepeque, Honduras, Central America.

Experiment Layout

Forest Road: Surface and cut & fill slopes

One Replicate

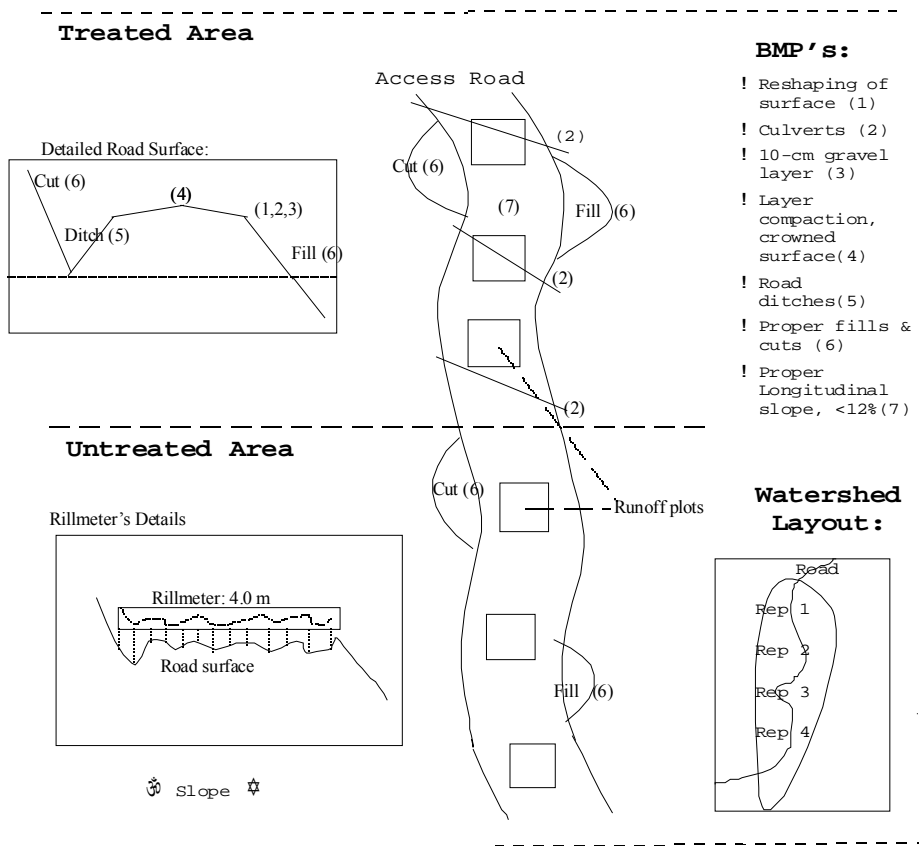


Fig. 3-2. Layout of the forest road experiments

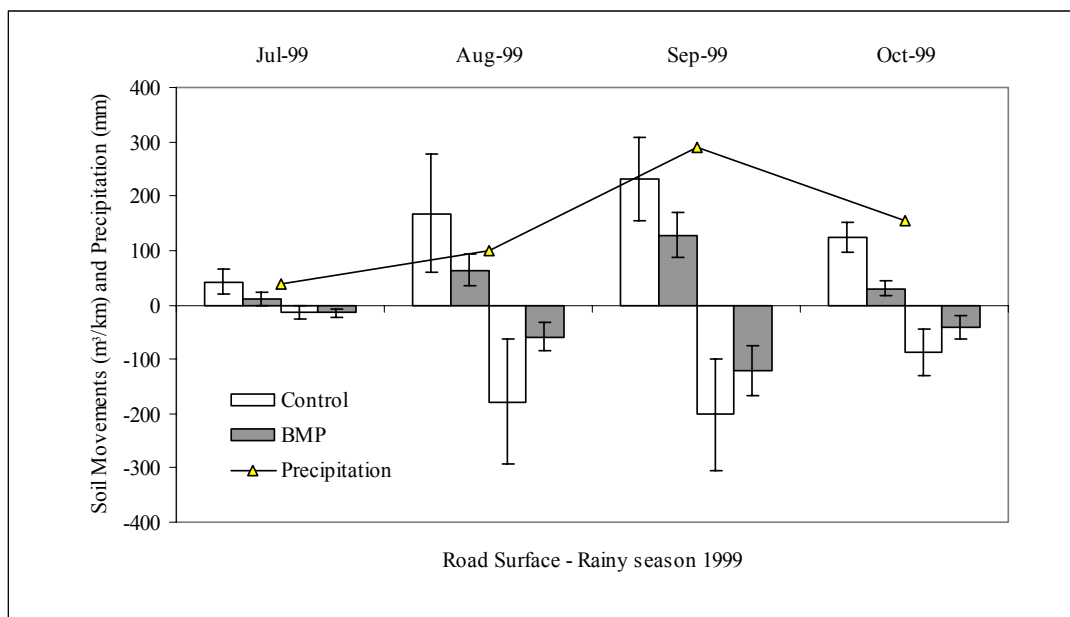


Fig. 3-3. Soil loss and deposition from the experimental road in 1999. BMP- treated road segments are compared with the untreated (control) road segments. Positive values represent soil loss and negative values indicate soil deposition along the road during the study period. Monthly precipitation values are also shown in the same Y axis.

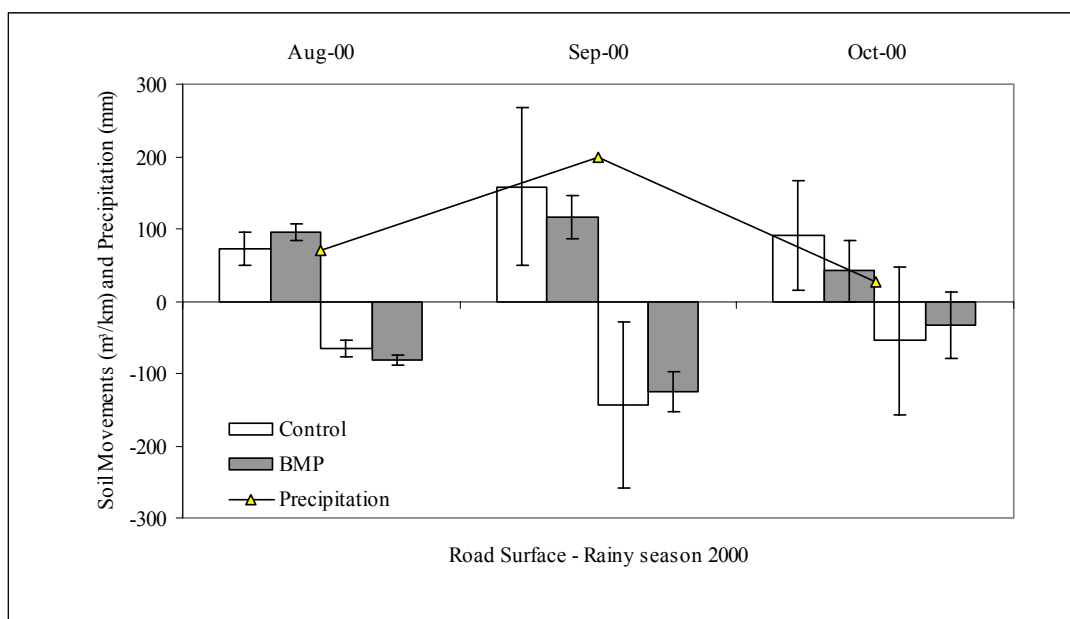


Fig. 3-4. Soil loss and deposition from the experimental road in year 2000. BMP- treated road segments are compared with the untreated (control) road segments. Positive values represent soil loss and negative values indicate soil deposition along the road during the study period. Monthly precipitation values are also shown in the same Y axis.

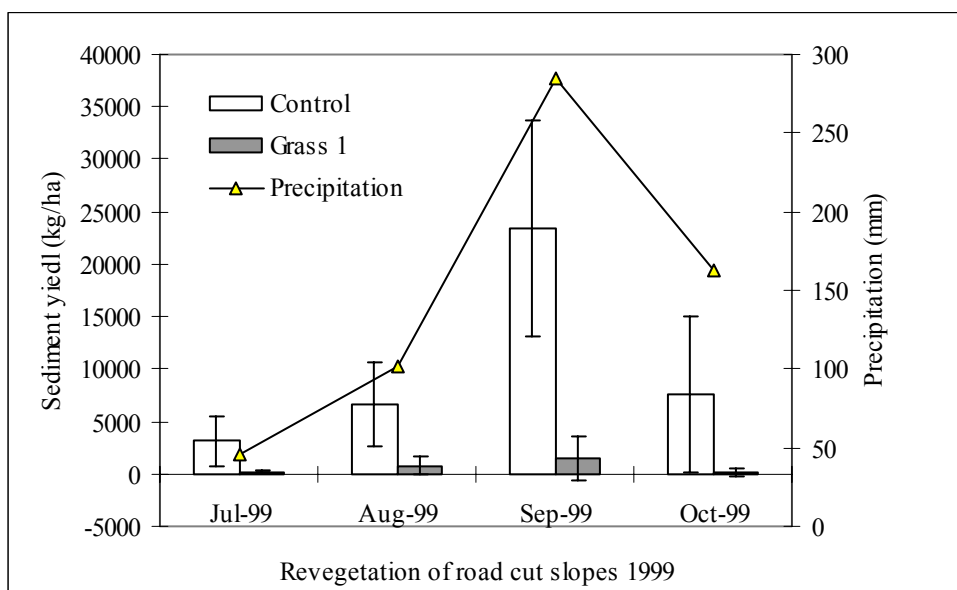


Fig. 3-5. Sediment yield from revegetated (Grass 1: *Hyparhenia rufa*, BMP) and non-revegetated (control) cut slopes from an experimental road in 1999. Precipitation values during the study period are shown in a second Y axis.

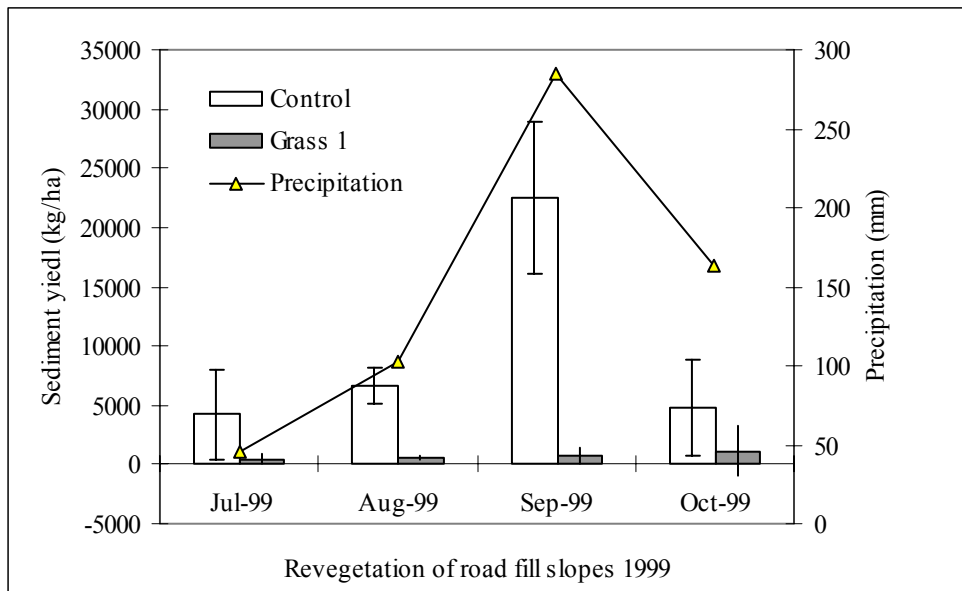


Fig. 3-6. Sediment yield from revegetated (Grass 1: *Hyparhenia rufa*, BMP) and non-revegetated (control) fill slopes from an experimental road in 1999. Precipitation values during the study period are shown in a second Y axis.

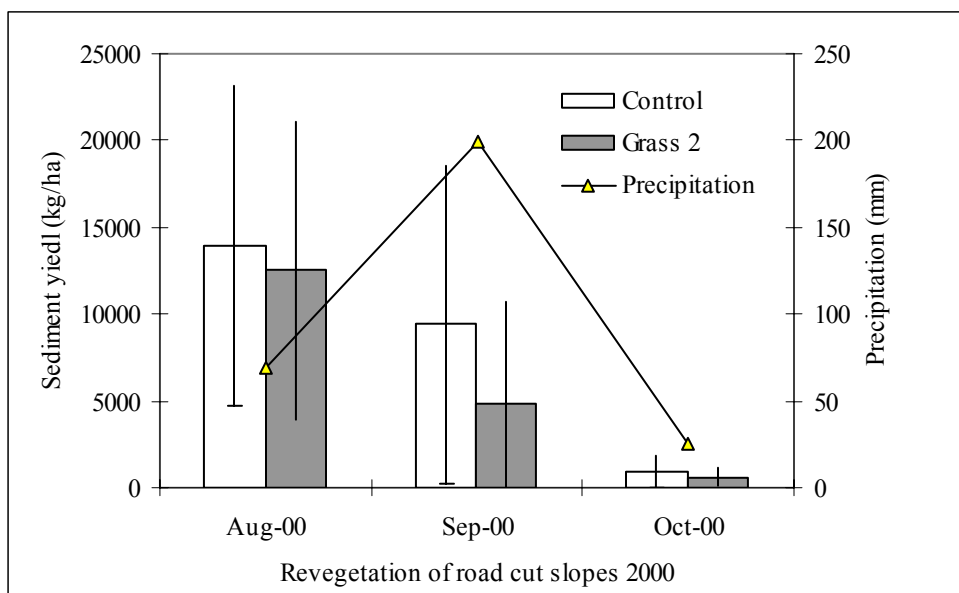


Fig. 3-7. Sediment yield from revegetated (Grass 2: *Vetiver zizanioides*, BMP) and non-revegetated (control) cut slopes from an experimental road in year 2000. Precipitation values during the study period are shown in a second Y axis.

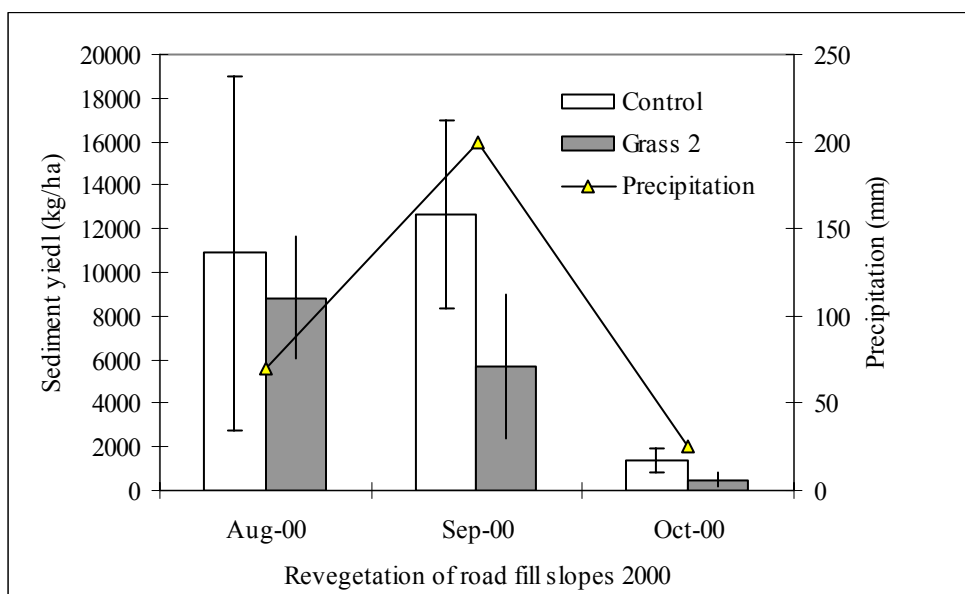


Fig. 3-8. Sediment yield from revegetated (Grass 2: *Vetiver zizanioides*, BMP) and non-revegetated (control) fill slopes from an experimental road in year 2000. Precipitation values during the study period are shown in a second Y axis.

CHAPTER 4
SUITABILITY OF THE WEPP MODEL AND THE UNIVERSAL SOIL
LOSS EQUATION TO PREDICT ACTUAL EROSION
IN THE FORESTLANDS OF HONDURAS³

Abstract

Two erosion prediction models were compared with measured erosion in standard plots of 22 m x 2 m in the central pine forest areas of Honduras. The models used in these experiments were the traditional Universal Soil Loss Equation (USLE), and the Water Erosion Prediction Project Model (WEPP). The purpose of this experiment was to determine the accuracy of model prediction in tropical forest lands to further introduce improvements and innovations in forestry Best Management Practices (BMPs). Model simulations were performed in a non-harvested forest and in a harvested forest. The final results showed a poor correlation between the models and the actual erosion in both scenarios. For the pine forest, the correlation coefficients (r) between the models and actual erosion were 0.80 for WEPP and 0.39 for USLE. Correlation coefficients for the harvested forest were: 0.29 for WEPP and 0.45 for USLE. The WEPP model predicted the real erosion rate slightly better than USLE for the non-harvested (undisturbed forest)

3. Coauthored by Samuel Rivera and Jeffrey L. Kershner.

site, while USLE showed a slightly better correlation for the harvested forest. Further changes should be made before researchers continue using these models in tropical

conditions including higher rainfall intensities, steeper slopes, and different types of soils. Improved or new models can be a feasible alternative to model erosion process and introduce rapid changes and innovations so as to improve the effectiveness of forestry BMPs.

Introduction

The rate of erosion on managed landscapes in the world varies from 20 to 100 times the natural erosion rate (Dudley 1995). In tropical regions, specifically in Latin America and the Caribbean, soil losses can reach 400 tons/ha/year (Toness et al. 1998). In Honduras, it is estimated that erosion has increased by 90% (from 400,000 ha to 760,000 ha) from 1972 to 1991 and erosion rates vary from 118 ton/ha/year on slopes between 9-25% to 760 ton/ha/year on slopes greater than 55% (Thurow and Smith 1998; Thompson 1992). Fifty percent of the suitable timber lands in Honduras are still covered by forests (Rivera et al. 1998); however, 75% of these forests are located on slopes greater than 30%. Erosion rates from forest sites can be less than 1 ton/ha/year if forest cover is maintained (Hudson et al. 1983), but once forests are converted to agricultural use erosion rates dramatically increase. Ultimately, these soil losses may cause sedimentation of stream channels and reservoirs and result in severe floods and water quality problems.

Erosion models are used to estimate the amount of soil loss and explore the effects of various treatments. A wide variety of simulation models have been used to predict erosion. The Universal Soil Loss Equation (USLE) and its other versions,

Modified Universal Soil Loss Equation (MUSLE) and Revised Universal Soil Loss Equation (RUSLE) are popular tools to estimate soil loss from agricultural and forestry activities (Brooks et al. 1991). Modified versions of the USLE were developed to improve the accuracy and precision of the USLE estimations (Brooks et al. 1991). New erosion prediction models have changed some empirical parameters to values based on more process-based calculations (Laflen et al. 1991).

The traditional USLE was developed as an empirically-based model to predict erosion hazards (Wischmeier and Smith 1978) and works as a function of four factors: soil erodibility, rainfall erosivity, topography and management. USLE estimates combine processes of overland flow over the course of a year from a hillslope. This model is based on approximately 8,000 plot-years of runoff, associated precipitation, and related data from 21 research projects scattered in the Midwestern U.S. (Ruppenthal et al. 1996).

USLE has become the most important tool in soil conservation planning throughout Latin America (Lal 1975; Lal and Elliot 1994; Alcala et al. 1998; Viana 1990; Silva 1997), but the use of USLE in Honduras has produced ambiguous results. For example, a test conducted on the El Nispero watershed found erosion rates ranging between 50 and 750 ton/ha/year (Molina 1989) which were very close to the actual erosion, while in the Southern region erosion was over estimated by 5 to 20 times the actual erosion (Thurrow and Smith 1998). Lal (1975) attributes these large disparities to the fact that this model was developed for temperate environments. All of these tests were conducted under agricultural conditions. Some applications of USLE have been

implemented on both temperate (Dissmeyer and Foster; 1985) and tropical forests (Viana 1990).

The WEPP model was developed by the Agricultural Research Service (ARS), the Soil Conservation Service (SCS), the US Forest Service (USFS) and the Bureau of Land Management (BLM) to accurately predict erosion rates from land use activities. The WEPP model estimates spatial and temporal distributions of soil loss and deposition and also provides an assessment of when and where erosion-deposition is occurring along the slope profile (Laflen et al. 1991). The model was originally developed to evaluate soil loss on agricultural and range lands (Chaves and Nearing 1996), but is believed to provide the best erosion prediction model for forested landscapes (Elliot et al. 1993; Laflen et al. 1991). Research is currently in progress to evaluate the application of WEPP to forest conditions, including harvested areas and forest roads (Elliot et al. 1995[a][b]). At present, input files have been developed to model road surfaces, timber harvested areas, forest fires, and forest cut slopes (Elliot 1996; Elliot and Hall 1997). Results have shown that the WEPP model is well suited to predicting erosion in a variety of forest conditions (Morfin et al. 1996; Foltz and Elliot 1996; Foltz 1996) and is useful in assisting managers in the design of water bar spacing and buffer zone widths adjacent to streams. The model has been used to predict the optimal cross drain spacing necessary to reduce stream sediment delivery and the USFS is currently using the model to design new guidelines for road cross-drains (Morfin et al. 1996; US Forest Service 1997[a]).

The objective of this study was to determine the utility of WEPP and the USLE models in helping forest managers in Honduras identify which BMPs are most needed

and where they should be placed to reduce erosion and sedimentation rates. A comparison was also made between a harvested site and an undisturbed forest (non-harvested site) during individual rainfall events that occurred during the rainy season of 2000.

Methods

This study was conducted in the pine forests of the National School of Forest Sciences (ESNACIFOR) located in the mountains of central Honduras, Central America (Fig. 1-1). The school forest is located 3.5 km to the southwest of the town of Siguatepeque, within the “El Cajon” watershed which supplies the nation’s largest reservoir which is the source for 70 percent of the country’s hydropower (Gollin 1994). The area is mountainous with elevations ranging from 540 to 2,500 m above sea level. Most of the forest is located on slopes greater than 40%. The soils are well-drained Lithosols of the series Cocona (Simmons and Castellanos 1969). Overstory species include Caribbean pine (*Pinus oocarpa*) and the understory is mixed grasses that are dominated by *Hyparhenia rufa*.

Six runoff plots were randomly established to measure the actual erosion at the site. Three plots were located in an unharvested (undisturbed) area of the forest and three plots were located in a harvest area. The harvest unit was clearcut two years previous to the measurement period. Slope (9%) and soil type (Lithosols, sandy loam texture, and a pH ranging from 5.0 to 6.0) were the same for all slopes, however, precipitation varied during the study period. Standard 2 x 22m-runoff plots (0.004 ha) were delineated by

strips of thin-gauge sheet metal (25 cm width) driven into the ground (7 cm) and a metal collector was dug into place at the lower end (McClurkin et al. 1987; Figueroa et al. 1983).

All plots were aligned with the slope of the unit and dimensions of the collectors were determined by calculating the maximum precipitation intensity for a recurrence interval of 5 years. Soil losses were measured in a calibrated container, starting all plots at the same time. The sediment collectors had a sediment trap to retain the coarser sediments. Measurements were performed daily and data were collected from August through October. Runoff volume, the amount of water in the metal collector, was recorded and a 1-liter sample (tank was stirred previously) was taken to the soil lab to determine suspended sediment (fine particles) distribution. Fine sediment content was determined following methods described by Kunkle and Thames (1976) and Brakensiek et al. (1979). Besides the observed sediment yield data, automatic rain gauge data, soil maps, and descriptions of conditions from onsite inspections were also recorded.

Several field measurements were taken to predict sediment values from the USLE model. The sediment yield is obtained from the following equation:

$$SY = R K L S C P$$

Where: SY = erosion loss in kg/ha, R = rainfall erosivity factor, K = soil erodability factor, L = slope length factor, S = slope gradient factor, C = vegetative and management factor, and P = erosion control practices factor.

Their product gives the estimate of soil loss measured at the end of the slope. The variables R, K, L, and S were determined using standard procedures described by Wischmeier and Smith (1978). The factor R was obtained from EI which is the storm energy times maximum 30-minute intensity. It was calculated using the following equation:

$$EI_{30} = 210.3 + 89 \log_{10} I$$

Where: EI_{30} = storm energy times maximum 30-minute intensity in tons per hectare per cm of rain, and I = rainfall intensity in cm per hour.

Values for C and P were estimated by the procedures described by Dissmeyer and Foster (1980) using a factor in which harvest areas can be considered to be similar to intensively managed farming systems. The measured values were plotted against the USLE estimated values.

To run the WEPP model, input information from the four files (slope, climate, management, and soil) had to be collected and input into the model. A database was generated for each scenario to use the WEPP hillslope profile model for the WEPP model estimations. The variables used by the four input files of the WEPP are shown in Table 4-1.

Climate and soil input files were developed using local conditions instead of using the pre-set scenarios (templates) available in the model. Most soil variables were obtained from the lab soil analyses while others were obtained from analytical methods (equations) based on field measurements. For the slope file, the uniform slope option

was used and the slope length (Overland Flow Element, OFE) was divided into four segments of: 0, 5, 10, 20, and 22.13 m. The gradient was 9% for all slopes. For the WEPP management file, the procedure described by Elliot et al. 1999, Elliot 1996, and Elliot and Hall (1997) was used. The biomass reduction due to the timber harvest was input in the residue management and harvest index values in the management file (harvest index = biomass removed/biomass present). Several runs of the WEPP model (at the hillslope level) were performed using the slope profiles in which the runoff plots were located.

The output of the WEPP model is divided in three parts:

1. Rainfall and runoff summary, rainfall events amount (mm), storm runoff events amount (mm).
2. On site effects: soil loss (kg/m^2), soil deposition (kg/m^2), and soil loss/deposition along the hillslope profile (kg/m^2).
3. Off site effects: sediment leaving profile (kg/m^2) and sediment characteristics: particle diameter (mm), specific gravity, particle composition (% sand, % silt, % clay, %OM), detached sediment fraction, and fraction in flow exiting.

Additionally, actual sediment yield, USLE sediment yield, USLE R factor, rain intensity, precipitation amount, WEPP sediment yield, and WEPP runoff were plotted against each other to establish possible correlations.

Results

Sediment yield from harvested and undisturbed forest areas

Harvested forest areas are most vulnerable when a reduction in cover is combined with intense rainfall events. In the undisturbed forest plots, 36 rainfall events were recorded from August to October of 2000, while 45 rainfall events were recorded at the harvested forest site (Table B-11 and B-12). Soon after the onset of the rainy season, many erosive storm events started to cause large runoff volumes and soil losses at the harvested forest site. At the undisturbed forest site, the forest cover not only reduced the inter-rill erosion, but also was associated with preventing the sloughing that occurred in the harvested site. The largest rainfall event at the undisturbed forest site was 40.2 mm per day and produced the sediment yield of 6.8 kg/ha (Figures 4-1, 4-2). The largest sediment yield at a harvested site was 81.6 kg/ha and was produced after a moderate rain event of 23.9 mm. Larger sediment yields were consistently produced at the harvested sites (Figures 4-1, 4-2). As expected, sediment yield increased with the amount of daily precipitation. Small storm events led to minimal soil loss, whereas bigger storm events resulted in extreme soil loss.

Observed versus predicted sediment yields

Both USLE and WEPP overestimated actual soil losses. USLE grossly over-predicted annual soil losses for both the natural and the harvested forest (Figures 4-3, 4-4). For the undisturbed forest, the correlation coefficients (r) between the models and actual erosion were 0.80 for WEPP and 0.39 for USLE. Correlation coefficients for the harvested forest were: 0.29 for WEPP and 0.45 for USLE. USLE did a fair job of estimating soil loss for the harvested forest treatment on the field research plots. In

general, USLE and WEPP both did a poor job of predicting the actual erosion of the treatments implemented in the research plots.

Linear regression analyses showed that the functional relationship between observed and predicted sediment yield values were low. Observed sediment yield values and the predicted values of both models showed large disparities and consequently, low correlation coefficients (Figures 4-3, 4-4). Although WEPP apparently did a better job of estimating annual soil loss for the undisturbed forest (0.80) (Figures 4-3), we eliminated the outliers and the relationship went down to 0.39, showing a lower relationship. In general, observed sediment yield and runoff volume values versus the predicted values of WEPP and USLE had poor correlations.

Relationship of sediment yield with other variables

We used correlation analyses of sediment yield versus a number of independent variables to determine the most important factors predicting sediment yield. These variables included USLE predicted sediment yield, USLE R factor, rain intensity, daily precipitation, WEPP predicted sediment yield, and WEPP runoff (Table A-14). Our analysis revealed that sediment yield was weakly correlated with all variables except the USLE R factor. This factor had correlation coefficients of 0.72 for the forested (natural) site and 0.84 for the harvested site (Fig. 4-5, 4-6). The other variables explained less than 50% of the variation in soil loss recorded in the erosion plots, and appear to have little influence on the actual sediment yield in both the natural and the harvested forest scenarios.

Discussion

The erosion prediction models in this study appeared to have little power to predict actual sediment yields from our study sites. There was poor correspondence between predicted sediment yields and actual sediment yields for both high and low erosion rates. These results are very consistent with the literature. For instance, Thurow and Smith (1998) applied USLE and RUSLE (Revised Universal Soil Loss Equation) in agricultural lands in Honduras. The USLE overestimated the actual erosion by almost 20 times, while RUSLE underestimated from half to one tenth the actual erosion. Under agricultural scenarios, Viana (1990), Guido-Lopez (1997), and Ruppenthal et al. (1996) found similar results in Colombia, Nicaragua and Brazil.

The USLE R factor showed the highest correlation among all variables with the actual erosion yield. These findings are very consistent with Lal et al. (1997), Silva (1997), Somarriba-Chang et al. (1999) and Ruppenthal et al. (1996) who found that the R factor of USLE equation explained between 59% and 81% of the variation in soil loss recorded in agricultural plots in South America. In Honduras, Mikhailova et al. (1997) also found that the R factor is a better predictor of soil losses. The R factor is highly influenced by the Erosion Index value (EI_{30}). This is an indicator of the kinetic energy for an individual storm event and I_{30} is the maximum 30-minute intensity of the storm event (Wischmeier and Smith 1978). Lal (1975) found correlation coefficients between this index and soil loss and runoff of 0.65 and 0.85, respectively. This relationship is particularly strong in the tropics where the majority of storms are classified as 'erosive'

storms (storm that exceeds 6.4 mm during a 15-min period [Wischmeier and Smith 1978]), while only 5 to 10 percent of temperate storms are erosive (Lal 1975). In general, soil losses in the tropics are more dependent on climatic variables, specifically the rainfall kinetic energy, rather than soil and topographic variables. Of the five USLE factors, only the R factor used to estimate soil loss varied in the calculations of USLE. The others, K, L, S, and C factors are intrinsic physical factors that did not change over time.

Observed sediment yield and runoff volume values showed little correlation with the WEPP predicted values. In contrast, the WEPP model predictions were highly correlated with actual sediment yield values in Mexican agricultural studies where correlation coefficients were 0.75 for the runoff and 0.86 for the sediment yield on corn plantations (Villar et al. 1998). These results are also very similar to US evaluations of the WEPP model performance indicating a coefficient of determination (r^2) between observed and predicted erosion of 0.77 for single storm events in agricultural settings (Zhang et al. 1996). Similar results have been found in applications in forest lands (Elliot et al. 1999). There has been no use of USLE and WEPP models in forest lands in Central and South America.

The original WEPP model appear to do a reasonable job of estimating sediment yield in the undisturbed forest, however, the correlation coefficient ($r=0.80$) was influenced by one outlier. After we eliminated the outlier the relationship became less clear ($r=0.39$). There may be several factors that influenced our results. First, the use of WEPP in forest landscapes is relatively new and there are few studies linking actual and

predicted erosion (Elliot et al. 1999). There are no other efforts to apply this model to forest lands in other countries, to our knowledge. If this model is to be widely applicable, it needs to be refined and adapted to tropical environments and different climate and land management regimes. Second, high intensity precipitation associated with tropical environments may have affected the results. For instance, Nearing et al. (1990) found that precipitation is a dominant factor in model response and it may be even more different for tropical scenarios. Third, calculations of infiltration and runoff rates continue to be problematic in WEPP. Rice et al. (1994) blamed the inaccuracy of the model on the Green-Amp equation, which calculates the infiltration rate and the consequent runoff. Finally, most of the empirical research built into the model was based on gentle to rolling slopes, since steplands are used in the agricultural applications used in the WEPP model. WEPP tends to over-predict erosion on steep tropical forestlands because the model was not designed for the high energy rainfalls of this area. In general, it is difficult to provide insight into the model structure. A detailed evaluation of a model's response in the tropics is necessary in order to yield more insight into the structure of the model and to be useful in redesigning management practices.

Conclusions

The results illustrate the need for incorporating more detailed inputs into erosion prediction models, especially designed for tropical conditions. The USLE and the WEPP model were primarily developed for croplands of the United States. Tropical regions present greater rainfall intensities, significantly greater slopes, and many different soil

types than those used in the model development. The use of these models without previous validations should be avoided.

The USLE equation needs to be revised before it can be used in tropical conditions. There could be large errors in the estimates of deposition and channel erosion compared to field observations. The time period for the evaluations needs to be longer and include several hydrological years. The USLE R factor seems to be very suitable for predicting erosion and can be used to predict areas with high potential erosion hazard. The C and P factors and their respective sub-factors, proposed by Dissmeyer and Foster (1980) for forest land conditions need to be revised and adapted for tropical conditions. The major problem in the use of USLE in tropical forest lands of Honduras is the soil data. The soil erodibility (factor K) in Honduras varies greatly from one site to another and could cause problems where data are incomplete.

The WEPP is a powerful model capable of predicting the erosion impacts of different levels of vegetation disturbances and vegetation removals. In forest lands, the attempt made by Elliot et al. (1999) to model forest management activities is relatively new in the United States. No other effort has been made to use it in forest lands of other countries. This model needs to be refined and adapted to tropical environments and different pre-set climate and land management files need to be developed. The results of this study should encourage the incorporation of tropical environmental conditions into model development for more useful prediction tools in the tropics.

The introduction of new models or the validation of the USLE and WEPP models for forest lands using local conditions can provide a very useful tool to re-design forestry BMPs

in different scenarios at a lower cost and less time. This information can also be used to assess BMPs by providing information about the on-site erosion and off-site sedimentation due to timber harvesting and road building activities.

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Table 4-1. Input requirements for WEPP Model (USDA-WEPP 1995; Elliot et al. 1993)

Input File	Contents
Slope	Pairs of point indicating distance from top of slope and respective slope.
Soil	For top layer: albedo, initial saturation, interrill, and rill erodibility and critical shear. For all layers: thickness, initial bulk density, initial hydraulic conductivity, field capacity, wilting point, contents of: sand, clay, organic matter, and rock fragments, cation exchange capacity.
Climate	For each day of simulation: precipitation amount, duration, time to peak rainfall, peak rainfall, maximum and minimum temperatures, solar radiation, average wind speed and direction.
Management	Type of vegetation, plant growth parameters, tillage sequences and effects on soil surface and residue, dates of harvesting or grazing, if necessary description of irrigation, weed control, burning, and contouring.

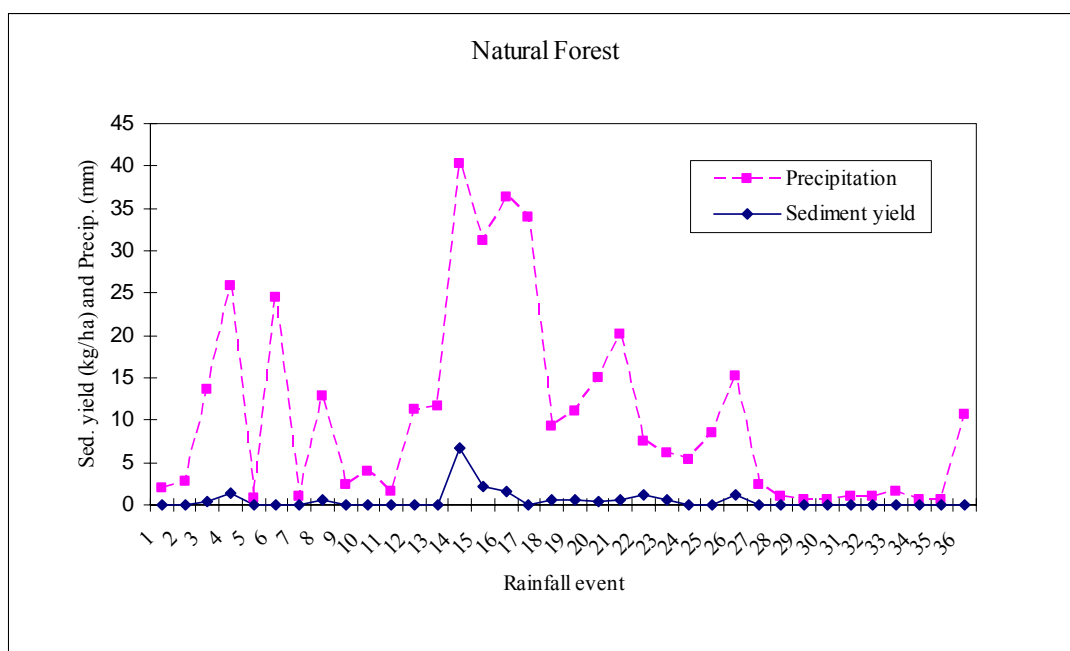


Fig. 4-1. Sediment yield from a natural (undisturbed) forest compared with the precipitation amount recorded during the study period (rainy season- year 2000). Precipitation and sediment yield values during the study period are shown in the Y axis.

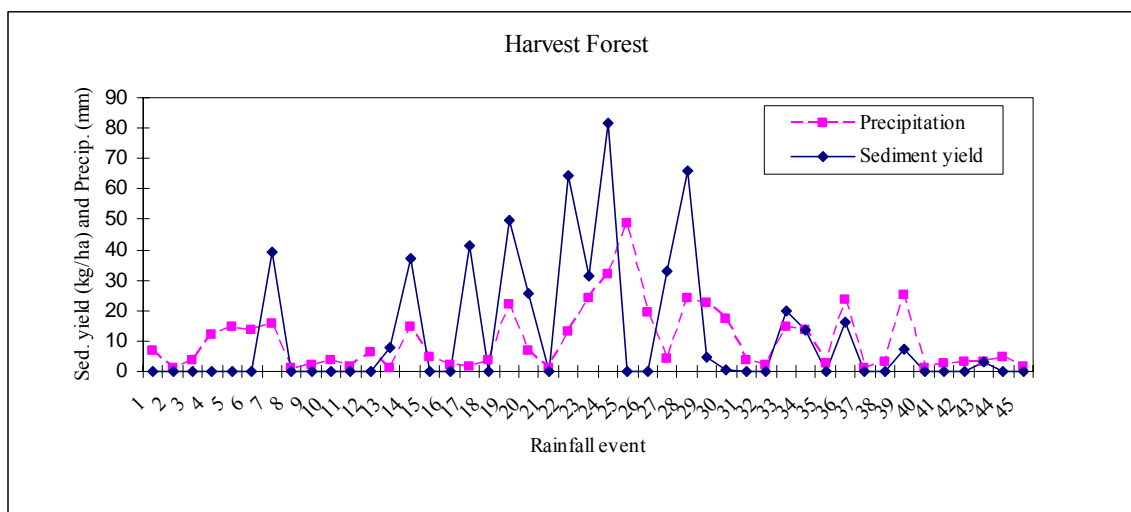


Fig. 4-2. Sediment yield from a harvested forest compared with the precipitation amount recorded during the study period (rainy season- year 2000). Precipitation and sediment yield values during the study period are shown in the Y axis.

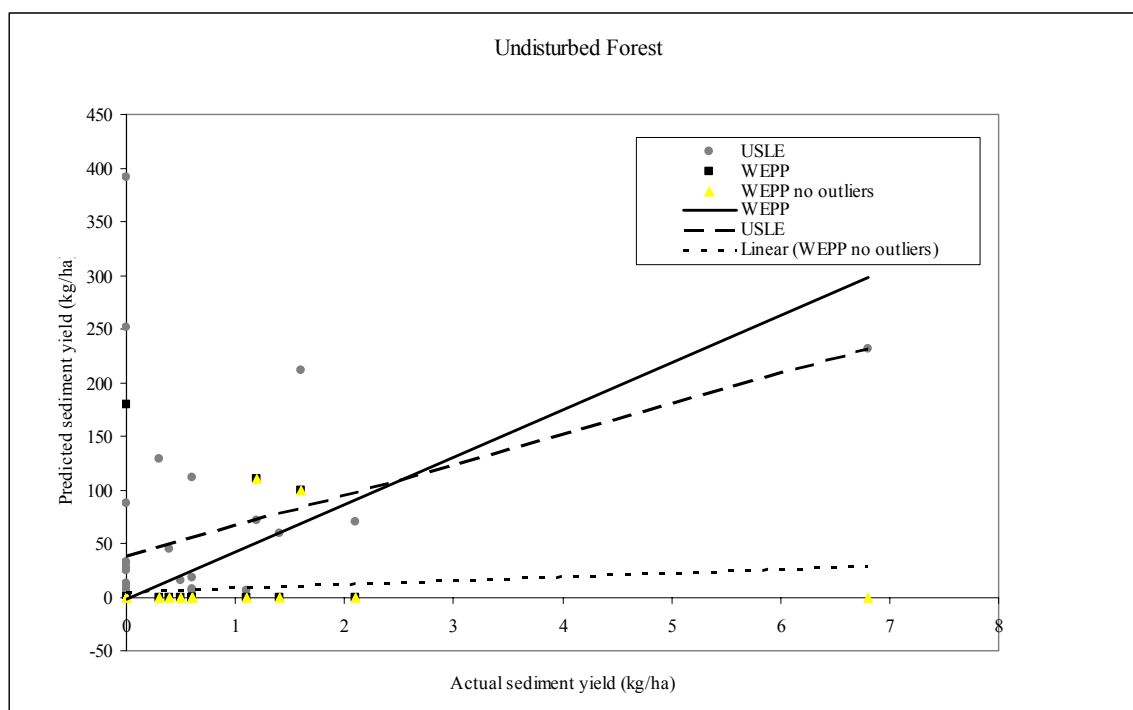


Fig. 4-3. Actual sediment yield from a natural (undisturbed) forest versus the predicted sediment yield using the USLE model ($r=0.39$) and WEPP model ($r=0.80$). The WEPP model correlation with no-outliers is also shown ($r=0.39$).

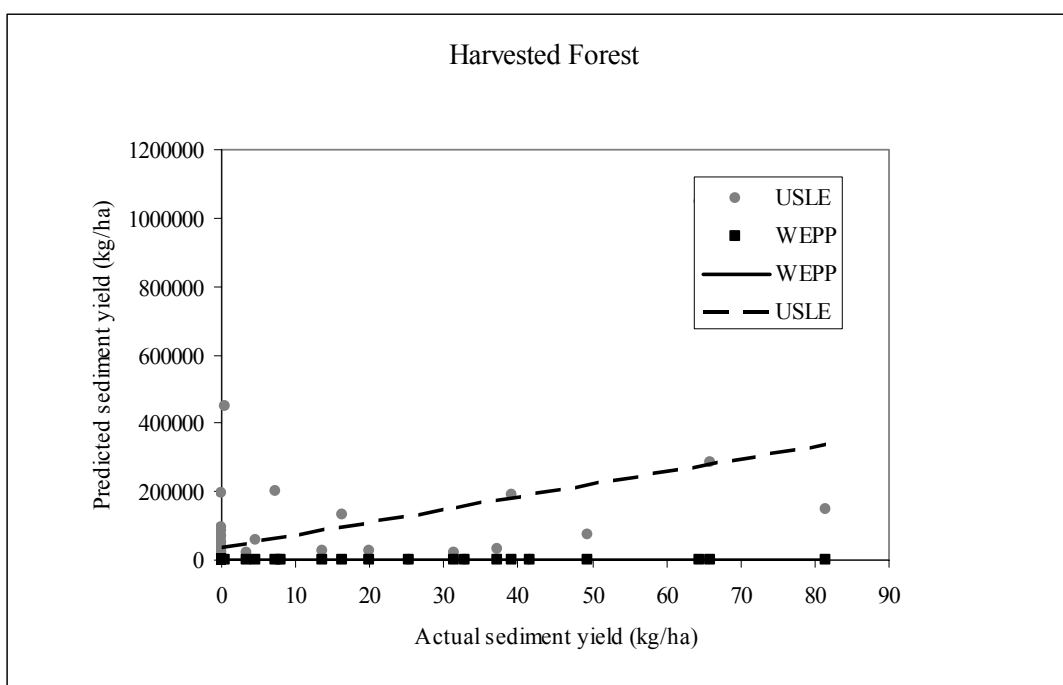


Fig. 4-4. Actual sediment yield from a harvest forest versus the predicted sediment yield using the USLE model ($r=0.45$) and WEPP model ($r=0.29$). The WEPP model trend line is drawn over the X Axis.

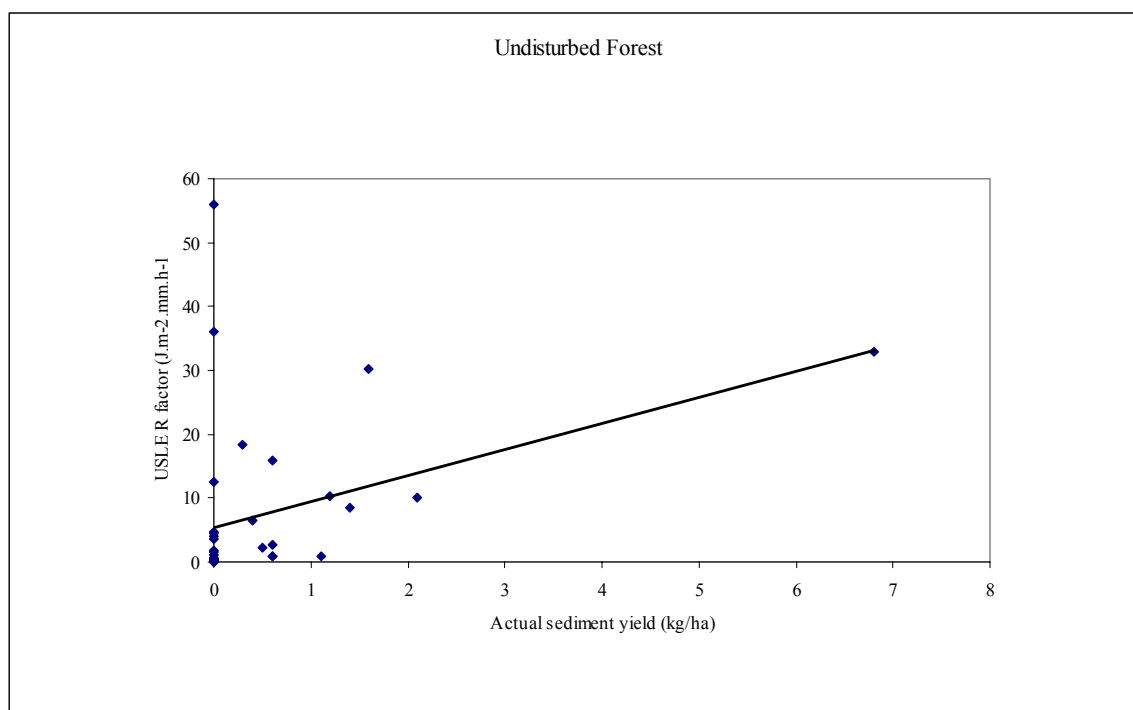


Fig. 4-5. Actual sediment yield from a natural (undisturbed) forest compared with the ULSE-R factor during the study period. Correlation coefficient = 0.72.

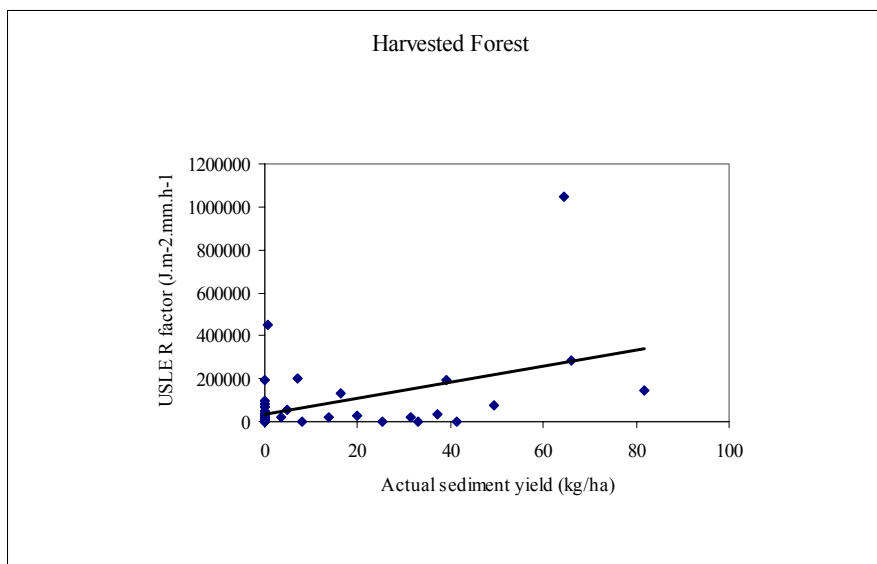


Fig. 4-6. Actual sediment yield from a harvested forest compared with the ULSE-R factor during the study period. Correlation coefficient = 0.84.

CHAPTER 5

SUMMARY

The results of this research project have provided insights and understanding of the complex hydrology processes that occur in the upper pine forested-watersheds of Honduras. Vegetation cover, especially forest, plays an important role in tropical landscapes in terms of water quality and quantity. The findings of this research show that runoff represents only 15 to 25% of the precipitation, thus demonstrating the important role of the vegetation in capturing the excess water and facilitating its infiltration into the ground. Unfortunately, when this process is disrupted by human-induced activities such as forest harvesting and road construction, water quality and quantity are also decreased.

Forestry Best Management Practices (BMPs) provide a feasible way to mitigate the adverse impact of forest activities on this complex cycle. BMPs improve infiltration and reduce runoff volumes, reducing the probability of soil particles being detached by concentrated volumes of water. BMPs such as cable logging and animal logging reduce the erosion produced by traditional tractor logging six to ten times. These environmentally sound methods avoid the excessive removal of soil and reduce sediment yield during the rainy season which corresponds to the most critical period for sediment production. Tractor logging should be avoided and/or minimized during this period.

Results also indicate that slash treatment, the chopping and scattering of harvesting residues forming a layer of 30 cm, proved to be the best post-harvesting BMP. It reduces erosion more than 100 times the erosion when compared to water bars. The

erosion rate is even lower than the erosion produced by an undisturbed forest. Water bars should be restricted to particular sites where they can be accompanied by other mitigation measures such as mini-check dams and rock or log barriers.

On forest roads, the erosion rate can be much higher than any other forest or agricultural activity, reaching sediment yields of 500 tons/km/year. The applied BMPs proved to reduce erosion by 50%. The results also show that road surfacing with washed and crushed gravel might be unnecessary when BMPs that provide a compacted base and a proper drainage are placed in the road prism. These BMPs are sufficient to reduce water penetration into the road surface allowing water to flow on both sides of the roads where it is evacuated by road ditches. Road surface sediment will eventually abandon the road surface and increase sedimentation at the stream channels levels if not properly mitigated.

At the road cut and fill slopes, re-vegetation measures were highly effective in reducing sediment yield. The propagation method (by slips) of the grass used to revegetate road side slopes might be the main factor ensuring the effectiveness of this BMP. When grasses propagate by root division and slips are buried into the ground, the erosion rates are higher than when the grass seeds are spread over the treated area and covered with harvesting residues. The first months of stabilization after planting are crucial in protecting the treated slopes.

The use of the erosion prediction models in this study revealed and confirmed the need of incorporating and developing new erosion models for the region. The Universal Soil Loss Equation (USLE) and the Water Erosion Prediction Project model (WEPP

model) showed a very poor correlation with the actual erosion. However, the study provided useful information on how real erosion occurs and how prediction models can be better simulated to mimic rain effects on soil detachment and transport. Rainfall intensity and duration are the main factors governing erosion. Within this variable, rain intensity is important, particularly the kinetic energy of individual storms. Soil type can be the second driving factor followed by topography. Land management activities appear to be the least important factors.

The introduction or adaptation of new models should provide a useful tool for re-designing forestry BMPs in different scenarios at a lower cost and in less time. Future models should use GPS, digital elevation models, and other GIS technologies to trace the soil particulate movements from the watershed divide to the lowest point in the stream channel. The information generated by these new models can be used to assess the efficiency of BMPs by providing information not only on the soil detached at the hillslope, but also on sedimentation and water quality impairment produced at the watershed scale.

APPENDICES

Appendix A.

ANOVA Tables

Table A-1. Analysis of log-transformed sediment yield for Watershed 1 in year 1999.

Tests of Fixed Effects				
Source	Num DF	Error term	F Value	<i>P>F</i>
Treatment	1	Rep(Treat)	10.22	0.0127
Time	4	Residual	95.82	<0.0001
Treatment*Time	4	Residual	5.34	0.0021
Covariance Parameter Estimates				
Parameter	Den DF	Estimate		
Rep(Treat)	8	0.5541		
Residual	32	0.1475		

Table A-2. Analysis of log-transformed runoff volume for Watershed 1 in year 1999.

Tests of Fixed Effects				
Source	Num DF	Error term	F Value	<i>P>F</i>
Treatment	1	Rep(Treat)	6.92	0.0302
Time	4	Residual	75.22	<0.0001
Treatment*Time	4	Residual	2.04	0.1123
Covariance Parameter Estimates				
Parameter	Den DF	Estimate		
Rep(Treat)	8	0.03871		
Residual	32	0.06411		

Table A-3. Analysis of log-transformed sediment yield for Watershed 2 in year 2000.

Tests of Fixed Effects				
Source	Num DF	Error term	F Value	<i>P>F</i>
Treatment	3	Rep(Treat)	37.34	<0.0001
Time	2	Residual	377.89	<0.0001
Treatment*Time	6	Residual	5.68	0.0004
Covariance Parameter Estimates				
Parameter	Den DF	Estimate		
Rep(Treat)	16	0.09117		
Residual	32	0.06357		

Table A-4. Analysis of log-transformed runoff volume for Watershed 2 in year 2000.

Tests of Fixed Effects				
Source	Num DF	Error term	F Value	<i>P>F</i>
Treatment	3	Rep(Treat)	22.86	<0.0001
Time	2	Residual	309.56	<0.0001
Treatment*Time	6	Residual	3.63	0.0073
Covariance Parameter Estimates				
Parameter	Den DF	Estimate		
Rep(Treat)	16	0.01889		
Residual	32	0.03971		

Table A-5. Analysis of variance of rainfall simulations in timber harvested areas.Runoff (m³/ha)

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Treatments (4)	3	77778897.40	25926293.13	17.33	<0.05
Error	16	23932812.80	1495800.80		
Total	19	101711692.20			

Sediment yield
(m³/ha)

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Treatments (4)	3	100033.09	33344.36	17.47	<0.05
Error	16	30532.63	1908.29		
Total	19	130565.72			

Time runoff began (min)

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Treatments (4)	3	107.56	35.85	7.05	<0.05
Error	16	81.42	5.09		
Total	19	188.98			

Table A-6. Analysis of soil losses for the road surface experiment in year 1999.

Tests of Fixed Effects				
Source	Num DF	Error term	F Value	<i>P>F</i>
Treatment	1	Rep(Treat)	10.19	0.0188
Time	3	Residual	17.75	<0.0001
Treatment*Time	3	Residual	1.28	0.3121
Covariance Parameter Estimates				
Parameter	Den DF	Estimate		
Rep(Treat)	6	868.00		
Residual	18	1888.12		

Table A-7. Analysis of log-transformed soil deposition for the road surface experiment in 1999.

Tests of Fixed Effects				
Source	Num DF	Error term	F Value	<i>P>F</i>
Treatment	1	Rep(Treat)	4.90	0.0687
Time	3	Residual	23.06	<0.0001
Treatment*Time	3	Residual	0.64	0.5982
Covariance Parameter Estimates				
Parameter	Den DF	Estimate		
Rep(Treat)	6	0.07092		
Residual	17	0.2967		

Table A-8. Analysis of soil losses for the road surface experiment in year 2000.

Tests of Fixed Effects				
Source	Num DF	Error term	F Value	<i>P>F</i>
Treatment	1	Rep(Treat)	1.02	0.3520
Time	2	Residual	3.72	0.0554
Treatment*Time	2	Residual	1.03	0.3861
Covariance Parameter Estimates				
Parameter	Den DF	Estimate		
Rep(Treat)	6	79.5000		
Residual	12	2925.22		

Table A-9. Analysis of soil deposition for the road surface experiment in year 2000.

Tests of Fixed Effects				
Source	Num DF	Error term	F Value	<i>P>F</i>
Treatment	1	Rep(Treat)	0.14	0.7254
Time	2	Residual	6.32	0.0134
Treatment*Time	2	Residual	0.33	0.7263
Covariance Parameter Estimates				
Parameter	Den DF	Estimate		
Rep(Treat)	6	0.0		
Residual	12	2717.17		

Table A-10. Analysis of log-transformed sediment yield of road cut slopes revegetated with *Hyparhenia rufa* in year 1999.

Tests of Fixed Effects				
Source	Num DF	Error term	F Value	<i>P>F</i>
Treatment	6	Rep(Treat)	29.56	0.0016
Time	18	Residual	8.24	0.0012
Treatment*Time	18	Residual	2.37	0.1048
Covariance Parameter Estimates				
Parameter	Den DF	Estimate		
Rep(Treat)	1	0.5069		
Residual	3	0.7584		

Table A-11. Analysis of sediment yield of road fill slopes revegetated with *Hyparhenia rufa* in year 1999.

Tests of Fixed Effects				
Source	Num DF	Error term	F Value	<i>P>F</i>
Treatment	6	Rep(Treat)	20.72	0.0039
Time	18	Residual	46.74	<0.0001
Treatment*Time	18	Residual	46.67	<0.0001
Covariance Parameter Estimates				
Parameter	Den DF	Estimate		
Rep(Treat)	1	6690502		
Residual	3	3253034		

Table A-12. Analysis of sediment yield of road cut slopes revegetated with *Vetiver zizanioides* in year 2000.

Tests of Fixed Effects				
Source	Num DF	Error term	F Value	<i>P>F</i>
Treatment	6	Rep(Treat)	0.49	0.5101
Time	12	Residual	7.31	0.0084
Treatment*Time	12	Residual	0.22	0.8023
Covariance Parameter Estimates				
Parameter	Den DF	Estimate		
Rep(Treat)	1	3582102		
Residual	2	42466861		

Table A-13. Analysis of sediment yield of road fill slopes revegetated with *Vetiver zizanioides* in year 2000.

Tests of Fixed Effects				
Source	Num DF	Error term	F Value	<i>P>F</i>
Treatment	6	Rep(Treat)	2.11	0.1968
Time	12	Residual	19.06	0.0002
Treatment*Time	12	Residual	2.06	0.1707
Covariance Parameter Estimates				
Parameter	Den DF	Estimate		
Rep(Treat)	1	6942698		
Residual	2	10387918		

Table A-14. Correlations coefficients among the studied variables in the natural undisturbed forest and the harvested forest.

Undisturbed forest

	USLE-R factor	USLE sed. Yield	Actual Sed.yield	Actual runoff	WEPP sed.yield	WEPP runoff	Rain intensity	Precip. amount
USLE R factor	1.00							
USLE sed.yield	1.00	1.00						
Actual sed.yield	0.39	0.39	1.00					
Actual runoff	0.31	0.31	0.73	1.00				
WEPP sed.yield	0.41	0.41	0.80	0.43	1.00			
WEPP runoff	0.41	0.41	0.79	0.39	0.98	1.00		
Rain intensity	0.72	0.72	-0.04	-0.09	0.10	0.10	1.00	
Precip. amount	0.67	0.67	0.67	0.76	0.66	0.66	0.31	1.00

Harvested forest

	USLE- R factor	USLE sed. Yield	Actual Sed.yield	Actual runoff	WEPP sed.yield	WEPP runoff	Rain intensity	Precip. amount
USLE R factor	1.00							
USLE sed.yield	1.00	1.00						
Actual sed.yield	0.46	0.46	1.00					
Actual runoff	0.43	0.43	0.84	1.00				
WEPP sed.yield	0.12	0.12	0.29	0.16	1.00			
WEPP runoff	0.11	0.11	0.03	-0.05	0.72	1.00		
Rain intensity	0.84	0.84	0.48	0.44	0.33	0.31	1.00	
Precip. amount	0.36	0.36	0.43	0.33	0.36	0.33	0.44	1.00

Appendix B.

Summary of field data

Table B-1. Sediment yield from timber harvesting experiments in Watershed 1 in year 1999.

Timber Harvesting Experiment		Variable: Sediment yield (kg/ha)				
Watershed 1 (1999)		Time (month-yr)				
Treatment	Rep	Jun-99	Jul-99	Aug-99	Sep-99	Oct-99
Cable	1	465	152	199	1233	478
Cable	2	307	80	306	1248	286
Cable	3	1020	93	205	3572	1002
Cable	4	438	63	310	912	530
Cable	5	676	105	187	483	494
	mean	581.20	98.60	241.40	1489.60	558.00
	std dev	278.71	33.68	61.16	1204.93	265.71
Precipitation (mm)		115	77	140	322	213
Tractor	1	5675	83	2091	39759	15311
Tractor	2	821	69	306	4476	1096
Tractor	3	567	162	247	3851	1198
Tractor	4	1565	265	435	11354	6489
Tractor	5	8183	970	1255	17117	9914
	mean	3362.20	459.20	866.80	15311.40	6801.60
	std dev	3394.48	411.31	796.00	14708.44	6044.60

Table B-2. Runoff volume from timber harvesting experiments in Watershed 1 in year 1999.

Timber Harvesting Experiment		Variable: Runoff (mm)				
Watershed 1 (1999)		Time (month-yr)				
Treatment	Rep	Jun-99	Jul-99	Aug-99	Sep-99	Oct-99
Cable	1	15.5	8	14.9	47.1	33
Cable	2	17.1	6	14.7	46.1	31
Cable	3	14.5	5	10.1	32.5	30
Cable	4	17.7	6	16.3	39.4	30
Cable	5	16.9	5	12.1	34.1	30
	mean	16.34	6.00	13.62	39.84	30.80
	std dev	1.31	1.22	2.48	6.69	1.30
Precipitation (mm)		115	77	140	322	213
Tractor	1	32.8	15	34	77.1	38
Tractor	2	18.3	7	18.7	52.9	28
Tractor	3	10.2	6	13.1	40.7	42
Tractor	4	28.4	12	27.1	75.7	42
Tractor	5	40.3	13	30.7	75.5	14
	mean	26.00	10.60	24.72	64.38	32.80
	std dev	11.89	3.91	8.64	16.63	11.97

Table B-3. Sediment yield from timber harvesting experiments in Watershed 2 in year 2000.

Timber Harvesting Experiment				
Watershed 2 (2000)		Variable: Sediment yield (kg/ha)		
		Time (month-yr)		
Treatment	Rep	Aug-00	Sep-00	Oct-00
Control	1	66	166	22
Control	2	149	516	40
Control	3	69	215	28
Control	4	103	155	22
Control	5	57	175	27
	mean	88.80	245.40	27.80
	std dev	37.91	152.96	7.36
Precipitation (mm)		117	220	62
Cable	1	66	450	38
Cable	2	78	343	46
Cable	3	53	226	39
Cable	4	60	302	38
Cable	5	73	278	36
	mean	66.00	319.80	39.40
	std dev	9.97	84.19	3.85
Tractor	1	290	692	79
Tractor	2	236	804	79
Tractor	3	547	2203	79
Tractor	4	1162	4358	165
Tractor	5	377	1173	111
	mean	522.40	1846.00	102.60
	std dev	376.45	1525.45	37.53
Animal	1	29	233	21
Animal	2	48	118	17
Animal	3	29	144	25
Animal	4	38	154	19
Animal	5	32	83	25
	mean	35.20	146.40	21.40
	std dev	8.04	55.65	3.58

Table B-4. Runoff volume yield from timber harvesting experiments in Watershed 2 in year 2000.

Timber Harvesting Experiment				
Watershed 2 (2000)		Variable: Runoff (mm)		
		Time (month-yr)		
Treatment	Rep	Aug-00	Sep-00	Oct-00
Control	1	2.9	6	1.5
Control	2	4.6	11.9	1.7
Control	3	3	7.6	1.5
Control	4	3.4	7.8	1.7
Control	5	2.3	8.8	1.7
	mean	3.24	8.42	1.62
	std			
	dev	0.86	2.19	0.11
Precipitation (mm)		117	220	62
Cable	1	3.2	8.8	2
Cable	2	4.4	9.2	2.3
Cable	3	3	7.8	2
Cable	4	3.3	7.3	2.1
Cable	5	2.9	7.8	2
	mean	3.36	8.18	2.08
	std			
	dev	0.60	0.79	0.13
Tractor	1	4.7	10.7	2.5
Tractor	2	5.6	13.7	2.6
Tractor	3	11.8	16.2	3
Tractor	4	13.1	34.7	2.6
Tractor	5	9.1	12	2.9
	mean	8.86	17.46	2.72
	std			
	dev	3.69	9.85	0.22
Animal	1	1.8	9	1.5
Animal	2	2.5	6.2	1.2
Animal	3	2.2	7.3	2
Animal	4	2.8	7.6	1.5
Animal	5	2.2	5.4	1.8
	mean	2.30	7.10	1.60
	std			
	dev	0.37	1.38	0.31

Table B-6. Summary of rainfall simulation data from timber harvesting experiments: total runoff volume, sediment yield, and soil texture.

REP'S	Treatment	TOTAL	Sediment yield (gr)		Soil Texture (%)		
		runoff (ml)	Wet Weight (g)	Dry Weight (g)	Sand	Silt	Clay
1	Traditional Harvesting	6200	89.7	69	60.69	28.78	10.53
2	Traditional Harvesting	4450	58.9	50	60.69	28.78	10.53
3	Traditional Harvesting	4484	80.9	73	50.56	36.88	12.56
4	Traditional Harvesting	8350	85	74	50.56	36.88	12.56
5	Traditional Harvesting	4050	90.1	74	52.59	32.83	14.58
	Standard Deviation	1792.3	12.87	10.27	5.24	4.05	1.69
	Mean	5506.8		68.0			
1	Water Bars	4280	91.3	73.1	63.13	29.99	6.88
2	Water Bars	5880	91.3	73.1	63.13	29.99	6.88
3	Water Bars	4750	87.3	65	61.1	34.04	4.86
4	Water Bars	4520	87.3	64	61.1	34.04	4.86
5	Water Bars	6140	97.7	75.4	65.15	29.99	4.86
	Standard Deviation	839.7	4.26	5.23	1.69	2.22	1.11
	Mean	5114.0		70.1			
1	Undisturbed forest (control)	10850	85	66	58.06	29.58	12.36
2	Undisturbed forest (control)	10275	80	75	58.06	29.58	12.36
3	Undisturbed forest (control)	9450	84	69	58.06	29.58	12.36
4	Undisturbed forest (control)	10630	84	69	58.06	29.58	12.36
5	Undisturbed forest (control)	10325	84	69	58.06	29.58	12.36
	Standard Deviation	532.7	1.95	3.29	0.00	0.00	0.00
	Mean	10306.0		69.6			
1	Slash Treatment	1420	55	42.1	72.85	18.64	8.51
2	Slash Treatment	3280	55	42.1	72.85	18.64	8.51
3	Slash Treatment	660	55	46	52.29	38.9	8.81
4	Slash Treatment	758	55	42.1	72.85	18.64	8.51
5	Slash Treatment	815	102.4	75	52.29	38.9	8.81
	Standard Deviation	1099.5	21.20	14.38	11.26	11.10	0.16
	Mean	1386.6		49.5			

Summary of runoff and sediment yield data

Treatment	Runoff (mm)		Sediment Yield (kg/ha)	
	Mean	STD DEV	Mean	STD DEV
Traditional Harvesting	5.5	1.7	1190	179
Water Bars	5.1	0.8	4850	360
Undisturbed forest (control)	10.3	0.5	100	15
Slash Treatment	1.4	1.1	30	9

Table B-7. Soil loss and deposition from forest road surface experiments in year 1999.

Forest Road Experiment / Road Surface Year: 1999									
Treatment	Rep	Soil loss (m ³ /km)				Soil deposition (m ³ /km)			
		Jul-99	Aug-99	Sep-99	Oct-99	Jul-99	Aug-99	Sep-99	Oct-99
Control	1	14	82	128	86	10	46	70	110
Control	2	68	76	238	132	16	122	224	86
Control	3	50	212	314	122	0	246	318	28
Control	4	34	302	240	152	28	300	194	126
	Mean	41.50	168.00	230	123	13.50	178.50	201.50	87.50
	Std dev	23.00	109.17	76.65	27.64	11.70	115.57	102.35	42.94
	Precipitation (mm)	39.5	99.5	288.5	154.5				
BMP	1	22	38	162	20	12	42	162	16
BMP	2	2	44	96	36	6	40	102	40
BMP	3	18	102	168	46	18	98	154	68
BMP	4	0	70	88	16	22	54	64	36
	Mean	10.50	63.50	128.50	29.50	14.50	58.50	120.50	40.00
	Std dev	11.12	29.18	42.34	13.99	7.00	27.05	46.11	21.42

Table B-8. Soil loss and deposition from forest road surface experiments in year 2000.

Forest Road Experiment / Road Surface Year: 2000								
Treatment	Rep	Soil loss (m ³ /km)			Soil deposition (m ³ /km)			
		Aug-00	Sep-00	Oct-00	Aug-00	Sep-00	Oct-00	
Control	1	132	40	62	130	74	104	
Control	2	32	176	52	96	118	98	
Control	3	90	234	118	6	226	8	
Control	4	40	182	130	32	158	8	
	Mean	73.50	158.00	90.50	66.00	144.0	54.50	
	Std dev	46.69	82.87	39.20	57.01	64.54	53.75	
Precipitation (mm)		69.4	199.5	25.8				
BMP	1	50	76	44	68	90	52	
BMP	2	50	96	16	22	100	8	
BMP	3	182	94	70	76	162	0	
BMP	4	98	198	36	164	150	72	
	Mean	95.00	116.00	41.50	82.50	125.5	33.00	
	Std dev	62.26	55.40	22.35	59.32	35.79	34.62	

Table B-9. Sediment yield from cut and fill slopes of forest road experiments in year 1999 using grass 1 (*Hyparhenia rufa*).

Forest Road Experiment					
First year (1999)			Sediment yield (kg/ha)		
Cut slopes		Time (month-year)			
Treatment	Rep	Jul-99	Aug-99	Sep-99	Oct-99
Control	1	3571	9524	25309	4992
Control	2	937	9680	36586	18518
Control	3	6283	6215	12131	2403
Control	4	1752	1145	19496	4409
	mean	3135.75	6641.00	23380.50	7580.50
	std dev	2369.52	3997.28	10323.84	7375.50
Precipitation (mm)		45.5	102	284.5	163
Grass 1	1	399	518	729	62
Grass 1	2	190	2159	4575	804
Grass 1	3	201	406	357	7
Grass 1	4	66	118	246	48
	mean	214.00	800.25	1476.75	230.25
	std dev	137.69	921.37	2075.80	383.21

Forest Road Experiment					
First year (1999)			Sediment yield (kg/ha)		
Fill slopes		Time (month-year)			
Treatment	Rep	Jul-99	Aug-99	Sep-99	Oct-99
Control	1	791	5212	15290	125
Control	2	1147	6044	19252	3696
Control	3	7216	6755	26017	5263
Control	4	7833	8651	29522	9935
	mean	4246.75	6665.50	22520.25	4754.75
	std dev	3795.98	1466.19	6434.54	4068.12
Grass 1	1	206	465	521	4267
Grass 1	2	105	741	518	81
Grass 1	3	1162	675	276	51
Grass 1	4	410	467	1658	80
	mean	470.75	587.00	743.25	1119.75
	std d	477.98	142.30	620.54	2098.21

Table B-10. Sediment yield from cut and fill slopes of forest road experiments in year 2000 using grass 2 (*Vetiver zizanioides*).

Forest Road Experiment				
Second year (2000)		Sediment yield (kg/ha)		
Cut slopes		Time (month-year)		
Treatment	Rep	Aug-00	Sep-00	Oct-00
Control	1	3753	2734	234
Control	2	11364	12839	901
Control	3	14764	20679	2287
Control	4	25857	1310	338
	mean	13934.50	9390.50	940.00
	std dev	9185.21	9109.08	944.59
Precipitation (mm)		69.4	199.5	25.8
Grass 2	1	3123	1207	171
Grass 2	2	15922	13569	1085
Grass 2	3	8367	2349	128
Grass 2	4	22731	2324	1066
	mean	12535.75	4862.25	612.50
	std dev	8590.46	5828.88	534.97

Forest Road Experiment				
Second year (2000)		Sediment yield (kg/ha)		
Fill slopes		Time (month-year)		
Treatment	Rep	Aug-00	Sep-00	Oct-00
Control	1	7278	12997	1713
Control	2	1903	6571	767
Control	3	13692	14815	1950
Control	4	20725	16368	995
	mean	10899.50	12687.75	1356.25
	std dev	8132.05	4304.25	564.96
Grass 2	1	7905	2925	280
Grass 2	2	5408	3376	166
Grass 2	3	11967	6278	774
Grass 2	4	10088	10092	780
	mean	8842.00	5667.75	500.00
	std dev	2827.75	3302.58	323.23

Table B-11. Sediment yield and runoff values from a natural pine forest, obtained using actual measurements and two predictive models: USLE and WEPP model.

Natural Pine Forest								
Event	R factor	USLE	Actual	Actual	WEPP	WEPP	Rain-	Precip
Date	J.m- 2.mm.hr-1	sy (kg/ha)	sy (kg/ha)	runoff (mm)	sy (kg/ha)	runoff (mm)	Intensity (mm/hr)	(mm)
8/1/2000	0.332	2.324	0.000	0.000	0.000	0.000	12.8	2.000
8/5/2000	0.540	3.783	0.000	0.000	0.000	0.000	14.8	2.800
8/7/2000	18.456	129.189	0.300	0.100	0.000	0.000	13	13.700
8/8/2000	8.545	59.815	1.400	0.300	0.000	0.000	11.4	25.900
8/9/2000	0.350	2.451	0.000	0.000	0.000	0.000	19.2	0.800
8/10/2000	55.881	391.165	0.000	0.000	0.000	0.000	48.8	24.400
8/17/2000	0.158	1.103	0.000	0.000	0.000	0.000	12.5	1.000
8/18/2000	15.813	110.688	0.600	0.100	0.000	0.000	28	12.900
8/19/2000	4.564	31.949	0.000	0.000	0.000	0.000	35	2.300
8/21/2000	1.507	10.550	0.000	0.000	0.000	0.000	15.2	4.000
8/22/2000	0.192	1.343	0.000	0.000	0.000	0.000	9.2	1.500
9/4/2000	4.651	32.557	0.000	0.000	0.000	0.000	19.2	11.200
9/5/2000	35.982	251.873	0.000	0.000	0.000	0.000	44.1	11.600
10/9/2000	32.972	230.801	6.800	0.300	340.000	8.300	16.3	40.200
9/12/2000	10.083	70.582	2.100	0.300	0.000	0.000	12.3	31.200
9/17/2000	30.221	211.544	1.600	0.300	100.000	2.100	20.4	36.300
9/18/2000	12.492	87.444	0.000	0.000	180.000	4.700	25.1	33.900
9/24/2000	0.934	6.538	0.600	0.100	0.000	0.000	8.5	9.300
9/25/2000	2.233	15.629	0.500	0.100	0.000	0.000	15.4	11.100
9/26/2000	6.401	44.809	0.400	0.200	0.000	0.000	14.1	15.000
9/27/2000	2.614	18.297	0.600	0.200	0.000	0.000	10.6	20.200
10/2/2000	0.909	6.360	1.100	0.100	0.000	0.000	10	7.500
7/10/2000	0.992	6.941	0.600	0.100	0.000	0.000	12	6.200
10/10/2000	1.764	12.345	0.000	0.000	0.000	0.000	12.8	5.300
10/11/2000	3.924	27.470	0.000	0.000	0.000	0.000	14.7	8.400
10/12/2000	10.267	71.869	1.200	0.200	110.000	1.000	19	15.200
10/16/2000	0.711	4.978	0.000	0.000	0.000	0.000	14.8	2.300
10/17/2000	0.057	0.396	0.000	0.000	0.000	0.000	2.4	1.000
10/18/2000	0.063	0.444	0.000	0.000	0.000	0.000	9.4	0.500
10/19/2000	0.037	0.257	0.000	0.000	0.000	0.000	5.8	0.500
10/20/2000	0.246	1.721	0.000	0.000	0.000	0.000	6.1	1.000
10/21/2000	0.485	3.394	0.000	0.000	0.000	0.000	17.4	1.000
10/22/2000	1.100	7.703	0.000	0.000	0.000	0.000	18.1	1.500
10/23/2000	0.226	1.580	0.000	0.000	0.000	0.000	11.4	0.500
10/24/2000	0.338	2.368	0.000	0.000	0.000	0.000	7	0.500
10/25/2000	3.520	24.637	0.000	0.000	0.000	0.000	22.7	10.700
Total		1886.898						

Table B-12. Sediment yield and runoff volume from a harvested forest, obtained using actual measurements and two predictive models: USLE and WEPP model.

Harvested Forest								
Event	R factor	USLE	Actual	Actual	WEPP	WEPP	Rain-	Precip
Date	J.m- 2.mm.hr-1	sy (kg/ha)	sy (kg/ha)	runoff (mm)	sy (kg/ha)	runoff (mm)	Intensity (mm/hr)	(mm)
8/1/2000	4.205	13875.276	0.000	0.000	0.000	0.000	14.7	6.900
8/4/2000	1.447	4776.016	0.000	0.000	0.000	0.000	9.3	1.300
8/5/2000	15.504	51161.674	0.000	0.000	0.000	0.000	19.2	3.600
6/8/2000	21.061	69501.929	0.000	0.000	0.000	0.000	24	11.900
8/7/2000	24.890	82137.922	0.000	0.000	0.000	0.000	21	14.700
8/9/2000	28.877	95292.608	0.000	0.000	0.000	0.000	27.3	13.700
8/10/2000	58.367	192611.510	39.200	39.200	0.000	0.000	40.8	15.800
8/17/2000	0.343	1130.405	0.000	0.000	0.000	0.000	12	1.000
8/18/2000	7.171	23665.500	0.000	0.000	0.000	0.000	16.1	2.300
8/21/2000	7.237	23881.671	0.000	0.000	0.000	0.000	14.4	3.600
8/22/2000	0.348	1147.523	0.000	0.000	0.000	0.000	9.8	1.500
8/23/2000	2.817	9294.565	0.000	0.000	0.000	0.000	14.1	6.400
9/3/2000	0.007	23.058	8.000	8.000	0.000	0.000	1	1.000
9/4/2000	10.407	34344.713	37.100	37.100	0.000	0.000	11.7	14.700
9/5/2000	10.534	34762.197	0.000	0.000	0.000	0.000	21.2	4.600
9/6/2000	7.939	26198.141	0.000	0.000	0.000	0.000	12.4	2.300
9/7/2000	0.253	834.856	41.500	41.500	0.000	0.000	10.2	1.500
9/10/2000	2.887	9525.646	0.000	0.000	0.000	0.000	14.9	3.800
9/12/2000	22.132	73036.098	49.500	49.500	940.000	2.400	40	21.800
9/13/2000	0.011	36.397	25.400	25.400	0.000	0.000	1.65	6.900
9/14/2000	0.434	1430.600	0.000	0.000	0.000	0.000	17.2	1.000
9/15/2000	316.698	1045102.248	64.500	64.500	0.000	0.000	97	12.900
9/16/2000	6.345	20937.404	31.300	31.300	0.000	0.000	19.7	23.900
9/17/2000	44.759	147704.541	81.600	81.600	0.000	0.000	44	31.800
9/18/2000	59.468	196245.317	0.000	0.000	0.000	0.000	21.3	48.600
9/20/2000	20.074	66244.519	0.000	0.000	0.000	0.000	29.4	19.600
9/25/2000	0.193	638.151	32.900	0.200	0.000	0.000	4.6	4.100
9/29/2000	85.929	283564.196	66.000	0.300	420.000	1.900	47	24.200
10/2/2000	17.068	56324.340	4.700	0.100	160.000	7.900	46	22.300
10/3/2000	136.867	451659.643	0.500	0.100	0.000	0.000	41.5	17.400
10/4/2000	4.444	14666.755	0.000	0.000	0.000	0.000	21.3	3.900
10/6/2000	6.575	21697.449	0.000	0.000	0.000	0.000	19.3	2.000
10/8/2000	8.375	27638.115	20.000	0.200	0.000	0.000	22.4	14.700
10/10/2000	7.250	23926.079	13.700	0.100	0.000	0.000	18.9	13.400
10/11/2000	6.920	22837.616	0.000	0.000	0.000	0.000	24.6	2.500
10/12/2000	40.148	132489.039	16.200	0.200	0.000	0.000	29.4	23.800
10/13/2000	0.536	1769.013	0.000	0.000	0.000	0.000	14.4	1.000
10/14/2000	14.844	48986.284	0.000	0.000	0.000	0.000	24.2	3.100
10/16/2000	61.447	202775.828	7.200	0.200	850.000	14.280	43.6	25.200
10/17/2000	0.372	1226.901	0.000	0.000	0.000	0.000	21.2	1.000

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10/19/2000	9.610	31711.656	0.000	0.000	0.000	0.000	19.3	2.500
10/21/2000	3.098	10224.175	0.000	0.000	0.000	0.000	21.2	3.000
10/22/2000	6.211	20497.234	3.400	0.100	0.000	0.000	42	3.000
10/25/2000	7.854	25919.357	0.000	0.000	0.000	0.000	16.1	4.800
10/30/2000	4.009	13230.005	0.000	0.000	0.000	0.000		1.500
Total		3616684.169						

CURRICULUM VITAE

Samuel Rivera
Ph.D. in WATERSHED SCIENCE

Personal Data

Born April 30, 1966 in Yoro, Honduras.

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Technical Background

Samuel Rivera is a natural resources management specialist with over 17 years of experience in forestry, watershed management, and training-research methodologies. His work has been concentrated in the Central American region on issues related to forest management-deforestation, erosion control practices, water quality and the management of drinking-water supply watersheds. He has worked on development issues with several international donors such as: the Canadian International Development Agency (CIDA), InterAmerican Development Bank and USAID. Mr. Rivera is also a research professor at the Research Department of ESNACIFOR (National School of Forest Sciences, Siguatepeque, Honduras). There he teaches (part time professor) several courses such as integrated watershed management, and forest hydrology for undergraduate students and research methodology for graduate students. He also serves as a private consultant for different projects throughout the country, working on the use of automatic climate stations, GIS and GPS technologies and the use of computer models for assessing soil and water balances under different management scenarios.

Academic Credentials

DOCTOR OF PHILOSOPHY in Watershed Science. Utah State University, 1996 to 2004. Logan, UT. USA.

MASTER OF SCIENCE in Watershed Science. Utah State University, 1994 to 1996. Logan, UT. USA.

BACHELOR OF SCIENCE in Forest Management. National Autonomous University of Honduras (UNAH), 1983 to 1987, La Ceiba, Honduras.

Professional Experience

2004-current: Programa PROMESAS, Canadian International Development Agency (CIDA): Honduras. Local Technical Advisor, Environment and water resources specialist.

Major duties include supervising watershed management projects in several areas of Honduras and assisting SERNA (Ministry of Environment) on watershed resources issues.

2003-2004: Programa MARENA, Ministry of Agriculture and Livestock and InterAmerican Development Bank (IADB): Honduras. Water resources specialist.

Major duties include the preparation of terms of references and follow-up of hiring processes of major studies on water quality, climatic stations and water budgets in 3 major watersheds of Honduras.

1998-current: National School of Forest Science (ESNACIFOR) Siguatepeque, Honduras

Worked on several tasks included: Research Professor: teaching Forest Hydrology and Watershed Management courses (current). Leader of a group of 6 researchers. Editor of TATASCAN (ESNACIFOR's scientific journal), Responsible for designing a research program and curriculum for a BS degree program in forestry-watershed management and for supervising their theses.

1999-2002: US Agency for International Development and National School of Forest Science (ESNACIFOR) Siguatepeque, Honduras

Coordinator of a component of the *Forestry Development Project*, a USAID sponsored program. Duties included: 1. Design and implementation of a 5-year watershed management plan of 4,200-ha-Rio Calan Watershed, which supplies drinking water for the city of Siguatepeque, 2. Conducting experiments in water quality and soil erosion practices related to my dissertation, in the 4,500-ha school experimental forest, 3. Awarding and supervising 35 small grants (US\$1-2,000 each) given to ESNACIFOR's senior students for research in watershed management related issues, 4. The reforestation of 334 ha of pine forest in the Guanaja Island, 5. Instructor in several training courses for municipal environmental technicians,

1996-1998: Utah State University Logan, Utah, USA

Research Assistant in the Watershed Science Unit and Ecology Center at Utah State University. My duties included the installation, monitoring, and analyses of laboratory experiments with the fish endangered specie: *Bonytail chub*, native specie of the Upper Colorado river. The experiments were: Flow training and Growth versus Temperature.

1988-1993: COHDEFOR (Honduran Forest Service) Tegucigalpa, Honduras

Five years of experience distributed in: 1. Supervisor of the watershed management section: supervise and oversee regional offices of the Honduran Forest Service regarding water quality issues and the implementation of Best Management Practices 2. Forest inventory crew leader supervising forest industries in the tropical rain forest, in Tela, Atlantida, Honduras.

Membership and Registration

Member of Executive Committee of MIS (Central American Integrated Management of Fragile Soils Consortium, sponsored by CIAT, International Centre for Tropical Agriculture).

Association of Forest Engineers of Honduras

Member of Society of American Foresters, 1994

Member of Soil and Water Conservation Society, 1996

Member of International Society of Tropical Foresters (ISTF), 1991

Scholarships

US Agency for International Development (USAID) for M.S. studies in the US. 1991.

Organization of American States, for Ph. D. studies. 1996.

US Agency for International Development (USAID) for Ph.D. studies completion, in the US. 2001.

Several travel fellowships, for training and conference attendance, awarded by USAID, CIAT (International Center of Tropical Agriculture) and ITTO (International Tropical Timber Organization).

Research Funding Obtained

U.S. Department of Agriculture, International Scientific Cooperation Exchange, USA, 1997. Grant for US\$ 27,000. 1998-2001.

Proyecto de Manejo de los Recursos Naturales de la Cuenca El Cajón, 1999-2000. Grant for US\$ 20,000 funding from Inter American Development Bank 787/OC-HO y 918/SF-HO.

CIAT-Hill Project. Grant for US\$ 4,000 funding to support thesis research projects at ESNACIFOR, 1999-2000.

Integrated Management of Fragile Soil Consortium (MIS). Grant for US\$15,000 funding to support thesis research projects at ESNACIFOR, EAP-El Zamorano, and UNA (Agrarian National University of Nicaragua) 2002-2003.

Publications

Chavez, J. L., R. Griffin, S. Rivera, and C. M. U. Neale, 2004. Watershed stream flow prediction using IWMI's world water and climate atlas and GIS techniques. Department of Biological and Irrigation Engineering, Utah State University. 30 p. *In prep.*

Rivera, S., J.L. Chavez and W.N. Martinez, 2003. The effect of land use dynamics on stream flow fluctuations: a SWAT simulation conducted in a third-order watershed of central Honduras. Submitted to the Second Conference: Watershed Management to meet Emerging Total Maximum Daily Load (TMDL) an event sponsored by ASAE and EPA, Albuquerque, New Mexico, USA. November 08-12, 2003.

Rivera, S., G.Sabillon, and M. Pineda, 2002. The effect of best management practices on discharge and water quality: a three-year study conducted in 28 small watersheds of central Honduras. Submitted and accepted to International Symposium on Land Use Change and Geomorphic, Soil and Water Processes in Tropical Mountain Environments. Sponsored by Katholieke University, Leuven, Belgium. Quito, Ecuador, 16-21 December, 2002.

Barbier, B., Hernández, A., Mejia, O., Rivera, S., 2002. Trade-Off Between Income and Erosion in a small watershed. GIS and Economic Modelling in the Rio Jalapa Watershed, Honduras. *In: Making Development Work*. Eds G.Leclerc and C.Halls. University of New Mexico Press.

Rivera, S., J.L. Chavez and R.I. Guillen, 2001. Mezcalar watershed sedimentation study and GIS based watershed management analysis. Submitted and accepted at the Environmental Regulations Conference: Watershed Management to meet Emerging Total Maximum Daily Load (TMDL) an event sponsored by ASAE and EPA, Fort Worth, Texas, USA. March 11-13, 2002 (Participant and speaker).

Rivera, S., A. Hernández, B. Barbier, O. Mejia, and S. San-martín, 2000. Trade-off between income and erosion in a small watershed: The Jalapa watershed, Honduras. Submitted and presented at National Conference of American Society for Photogrametry and Remote Sensing (ASPRS), Washington D.C., USA. May/2000. (Participant and speaker).

Rivera, S., L. M. Martinez, and G. Sabillon, 1999. Multitemporal analysis of deforestation in Honduras using GIS and remote sensing techniques. Submitted and presented at 1999 Society of American Foresters Annual Conventions Proceedings. Portland, OR, USA. (Participant and speaker).

S. Rivera y A. Oliva, 2004. Pago por Servicios Ambientales (PSA) en Cuencas Hidrográficas: La Experiencia del Programa MARENA en Honduras. Presented at II Simposio Iberoamericano de Economía Forestal 18 -21 Septiembre del 2004. Barcelona, España (Participant and speaker).

Hernández, A. S. Rivera, S. Velásquez, y F. Jiménez, 2004. Dinámica del uso de la tierra y de la oferta hídrica en la cuenca del río Guacerique, Tegucigalpa, Honduras. Manuscript sent to: Revista Recursos Naturales y Ambiente, CATIE, Turrialba, Costa Rica.

Three articles will be submitted to US Journal for publications this year. The articles are related to the 3 years of research conducted in Honduras about the testing of forestry Best Management Practices to reduce erosion and protect water quality in streams. The articles are part of my dissertation research project and will be coauthored by my major professor: Dr. Jeffrey L. Kershner (kershner@cc.usu.edu):

- Rivera, S., J.L. Kershner, and J. P. Dobrowolski, 2004. Testing best management practices in forest harvesting activities in Honduras. Manuscript submitted to Journal of Forest Science.
- Rivera, S. and J.L. Kershner, 2004. Testing forest road best management practices to reduce erosion in Honduras. Manuscript submitted to BIOTROPICA.
- Rivera, S. and J.L. Kershner, 2004. Suitability of the WEPP model and the Universal Soil Loss Equation (USLE) to predict actual erosion in the forestlands of Honduras. Manuscript submitted to Journal of Soil and Water Conservation.

14 articles (in Spanish) co-authored with ESNACIFOR's students in Revista Científica TATASCAN.

Escuela Nacional de Ciencias Forestales. Siguatepeque, Honduras. They can be seen at www.esnacifor.hn